



**CHIPS P-1051**

**CHerenkov detectors In mine PitS**

Physics soon and Physics later

3-5 year R&D program

An idea to strengthen the FNAL program at NuMI and LBNE

$\delta_{\text{ChiPs}}$

# Roadmap

- Introduction : why we need CHIPS and why now
- The physics goals of the CHIPS program
- The first step : CHIPS-M
- The next step : CHIPS-10
- Summary : the future is bright but its not orange

- FNAL has the best neutrino oscillation beam for the coming 30 years (NuMI now and LBNF later)

BUT!

- WE NEED BIGGER DETECTORS to make measurements in a human lifetime
  - Maybe factor 2 from beam power in the future, but history is always repeated : THERE ARE NEVER ENOUGH PROTONS
  - With present detector ideas, measurements will be **statistics limited** for a very very long time
- WE NEED CHEAPER DETECTORS because our physics is presently **limited only by money**
  - CHIPS combines the idea of a cheaper design and a huge detector mass

AND!

- RECYCLE THE DETECTORS for use in any neutrino beam, now in NuMI, later in LBNF
- CHIPS could cement FNAL's position to be first to measure  $\delta_{CP}$ .

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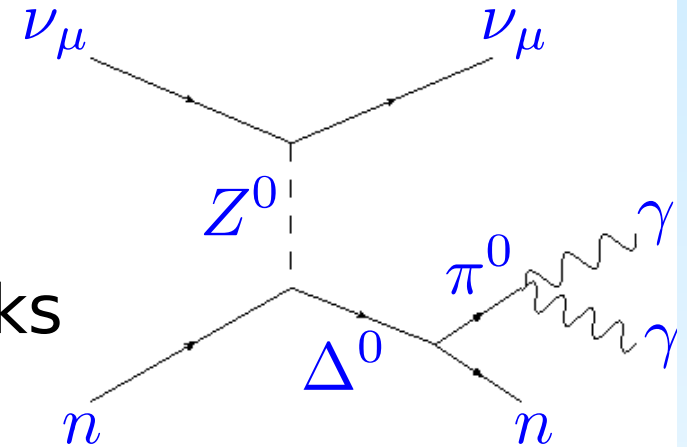


# Orientation

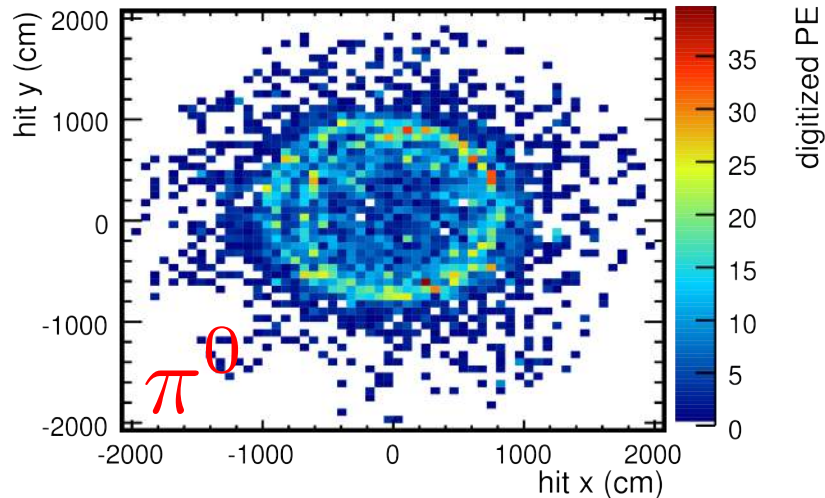
- CHIPS is a water Cherenkov detector which will be sunk in a flooded mine pit in the path of the NuMI beam
- Its main **physics goal** is to constrain or measure  $\delta_{\text{CP}}$  using NuMI neutrinos
- Its main **development goal** is to chart a new path towards cost effective Megaton neutrino detectors, hoping to get to \$200k/kt (presently \$1M/kt)
- It will comprise a series of prototypes which will deliver physics results and demonstrate real costs
- It will complement NOVA (being more on-axis) and LBNE (more off-axis) when LBNE comes online.

# Orientation II

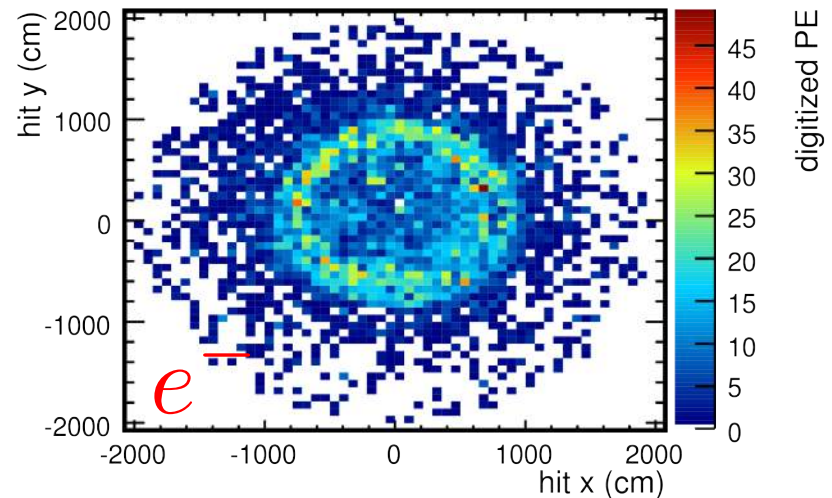
- Main background to  $\nu_e$  CC appearance is  $\nu_\mu$  NC  $\pi^0 \rightarrow \gamma\gamma$
- Need to distinguish multiple tracks from a single  $e^-$  track



Detector response from  $\pi^0$  event (top cap)

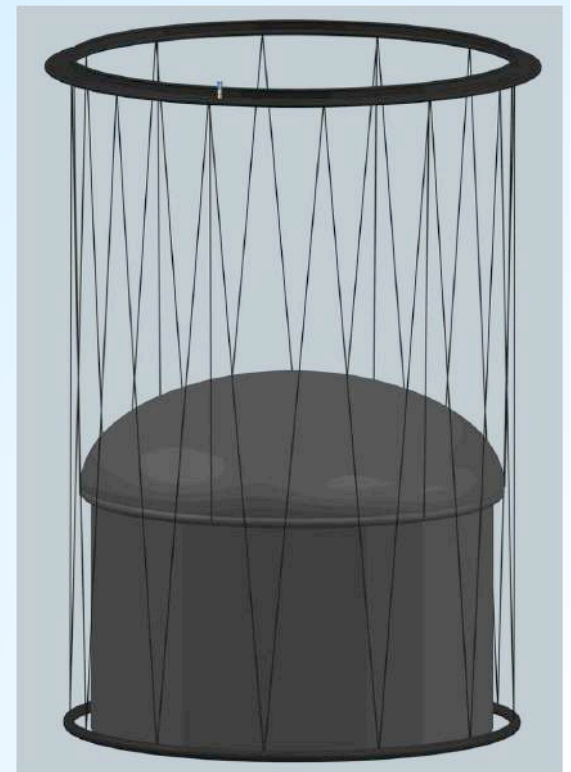
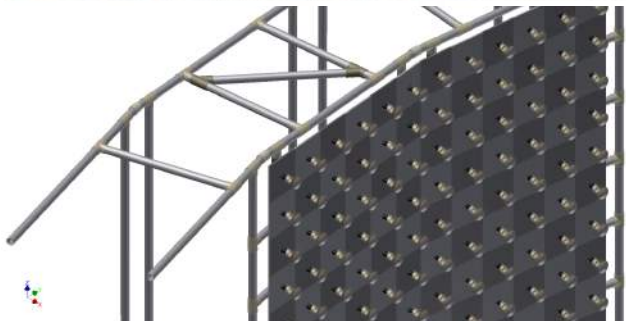


Detector response from  $e^-$  event (top cap)



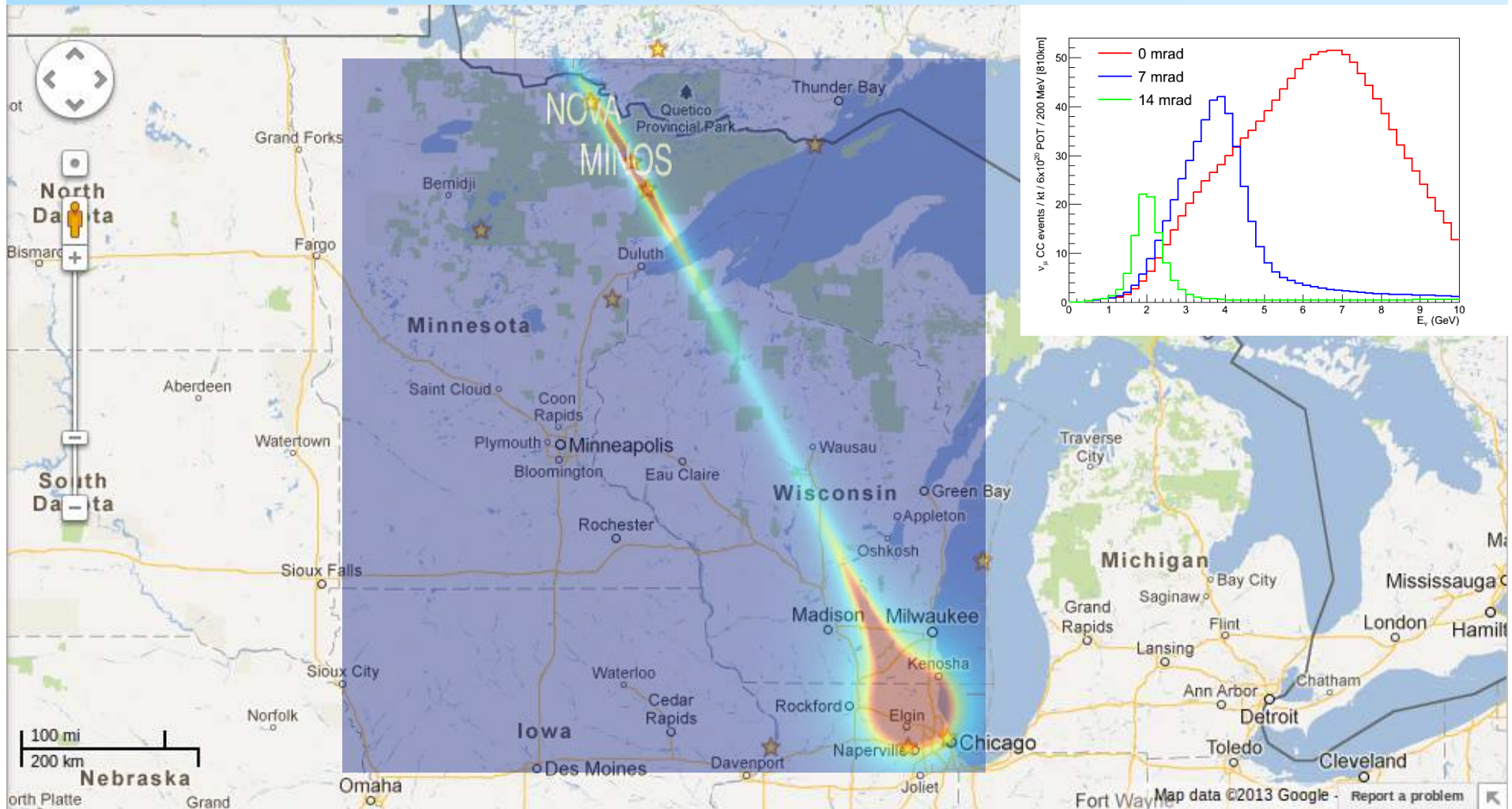
# CHIPS Detector Concept

- CHIPS is a water Cherenkov detector which will be sunk in a flooded mine pit in the path of the NuMI beam : water will provide mechanical support
- Will borrow heavily from commercially available aquaculture industry components where possible



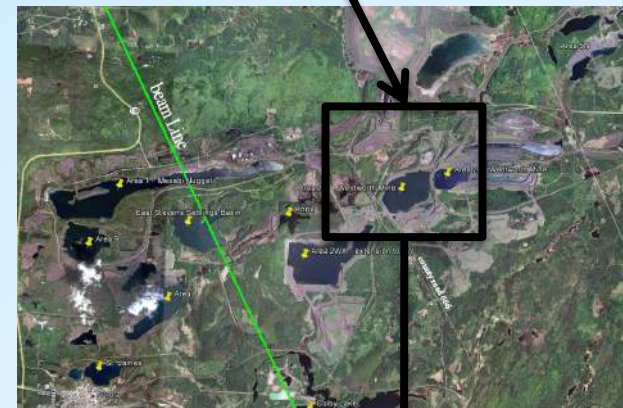
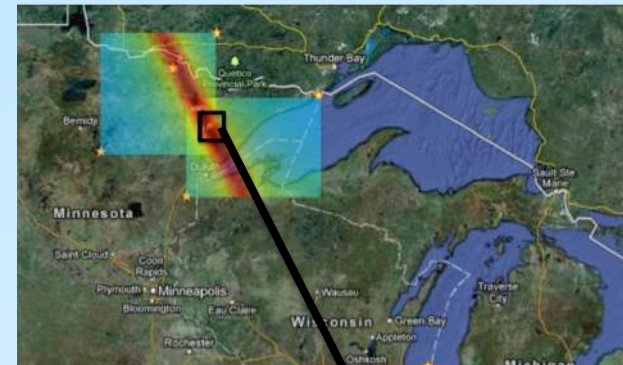
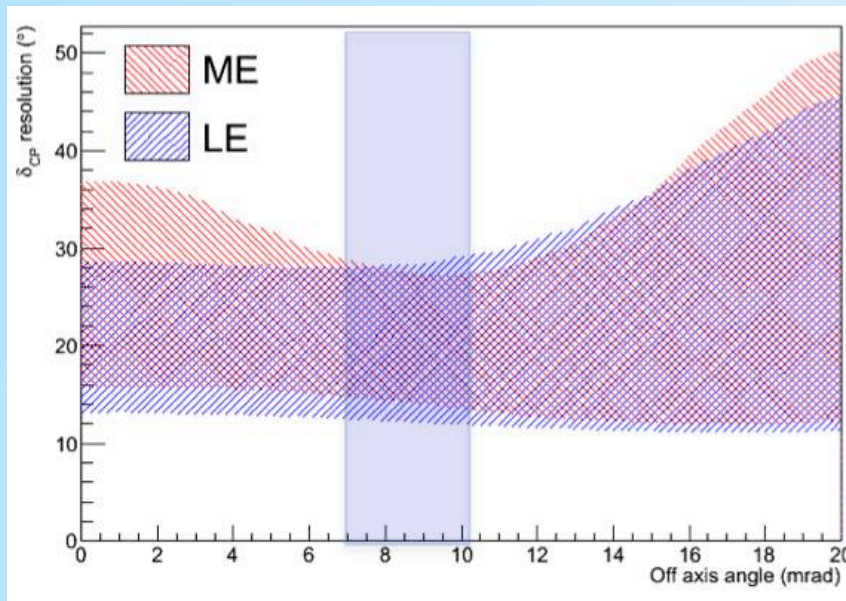


# Looking At the NuMI Beam : Flux at the surface



# CHIPS : Ingredients

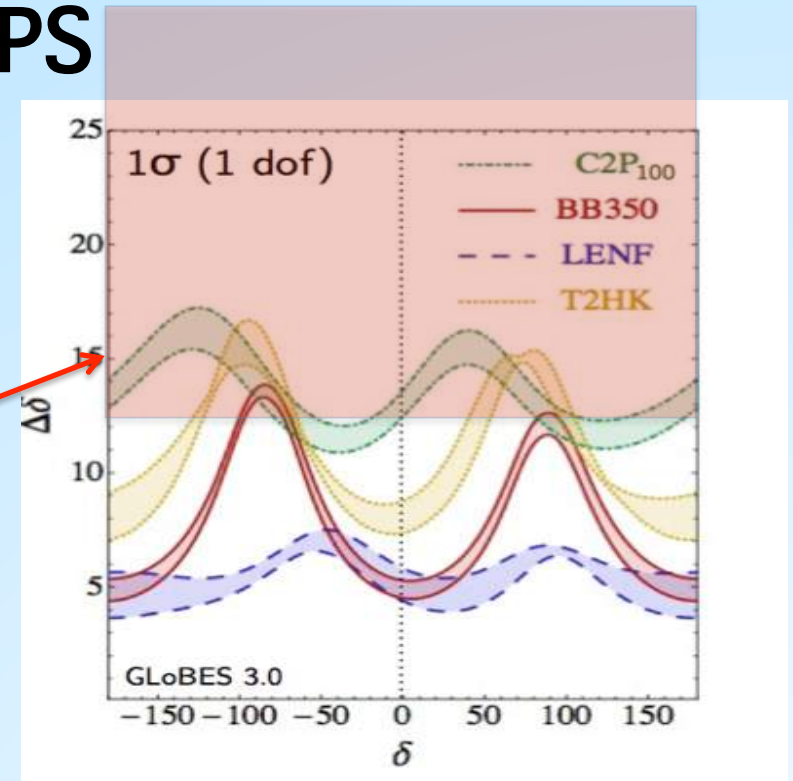
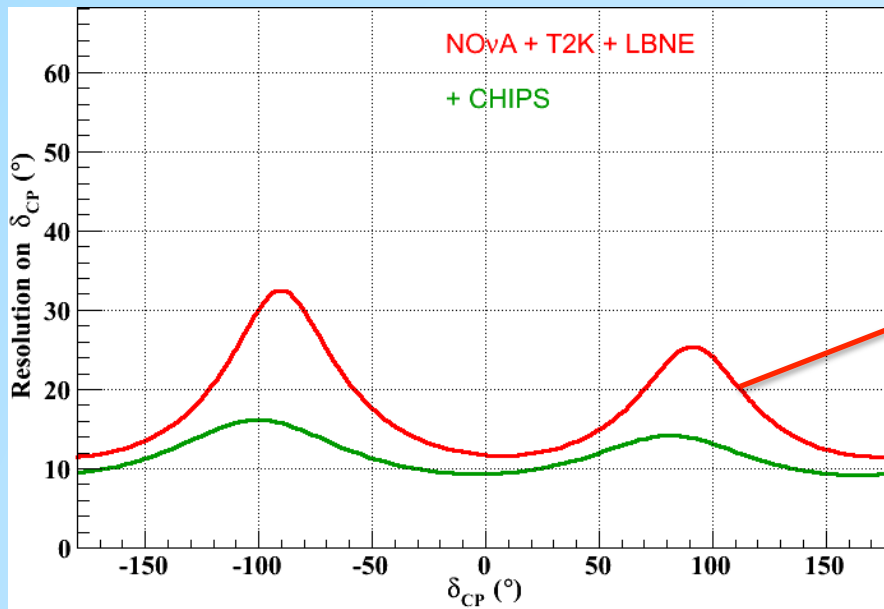
- Deep lake or body of water
- High energy neutrino beam
- Secure environment
- At 7mrad off axis
- Wentworth 2W is the solution







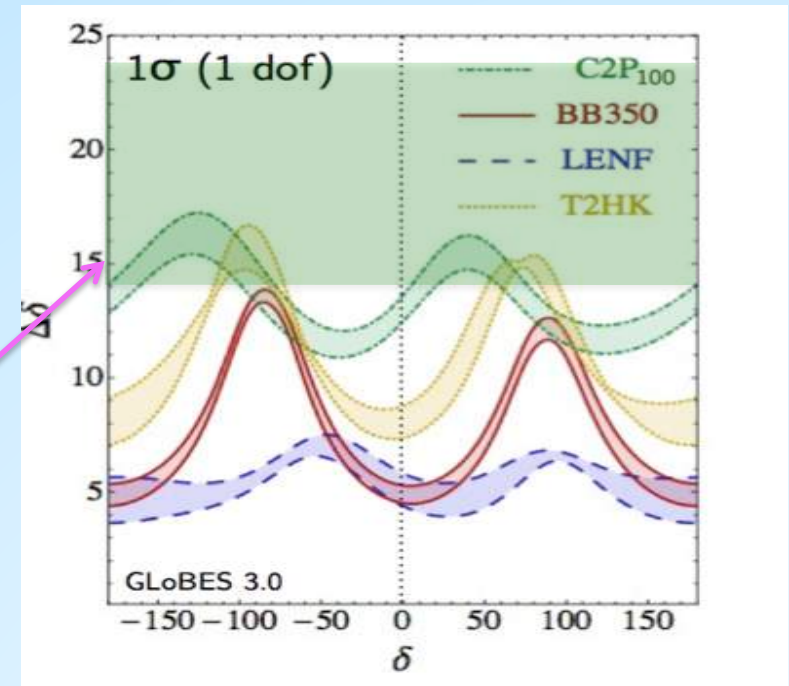
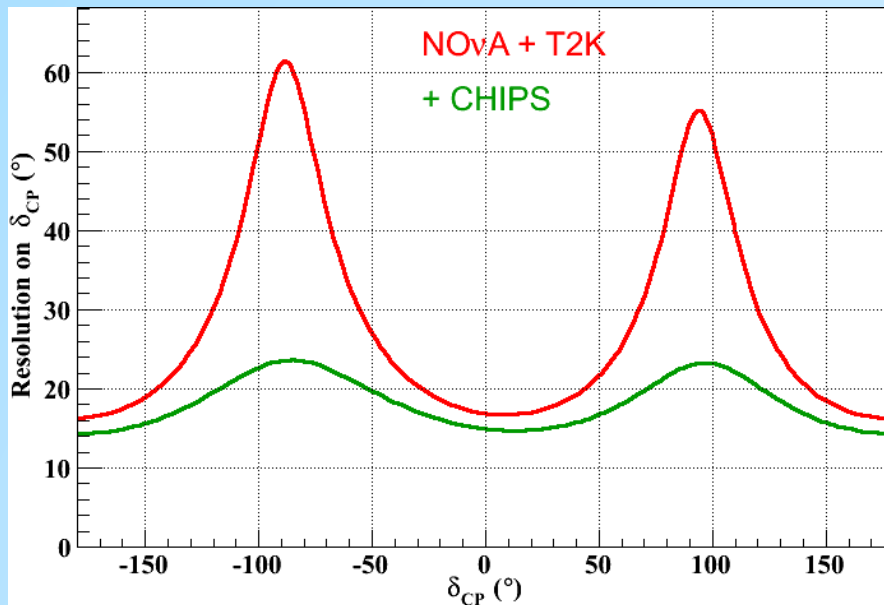
# NO CHIPS



P.Colomba, Neutrino 2012

- Without CHIPS, reach of T2K, NOVA and LBNE(10kt) in **2037** is pink shaded region

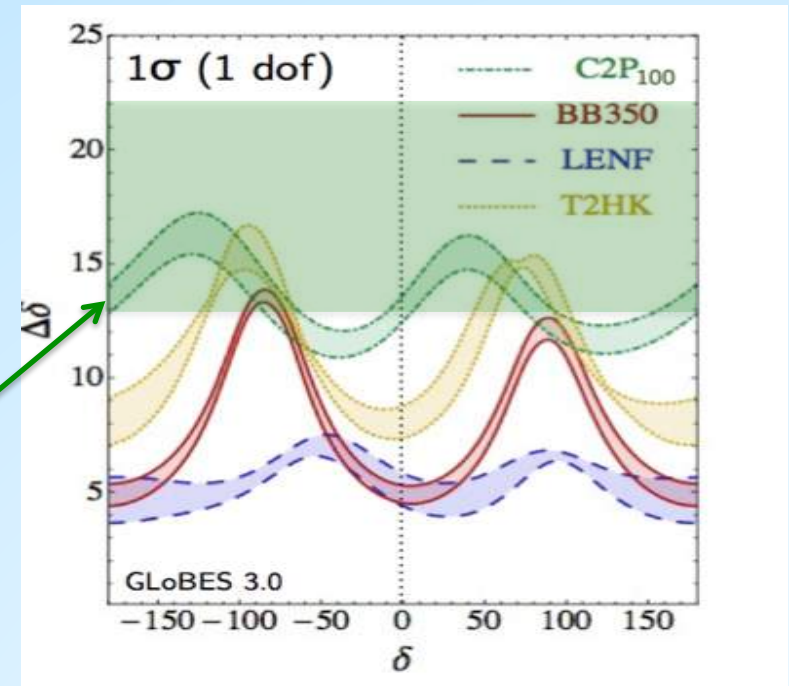
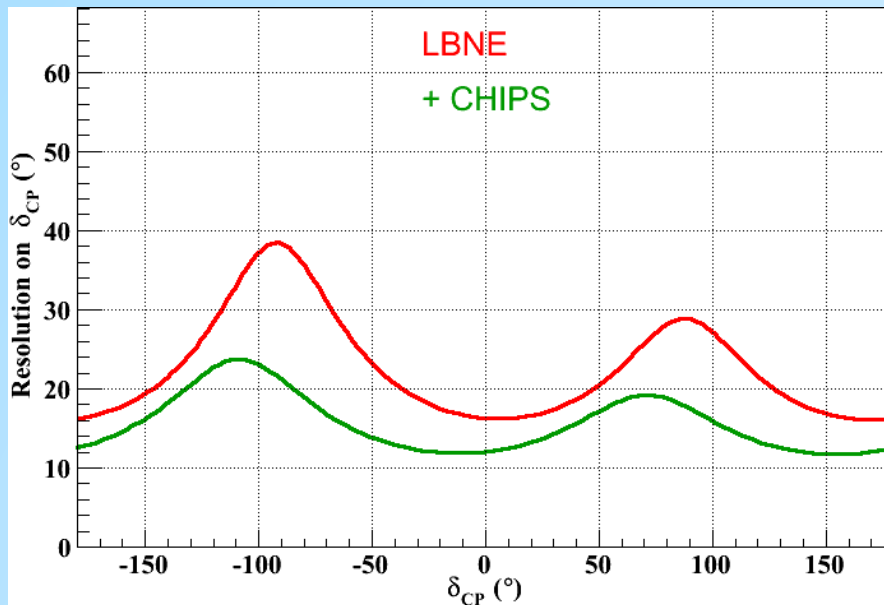
# 100kt CHIPS@NuMI



- With CHIPS@NuMI, reach of T2K, NOVA and CHIPS by **2026** (assuming 5 year lead time) is green shaded region

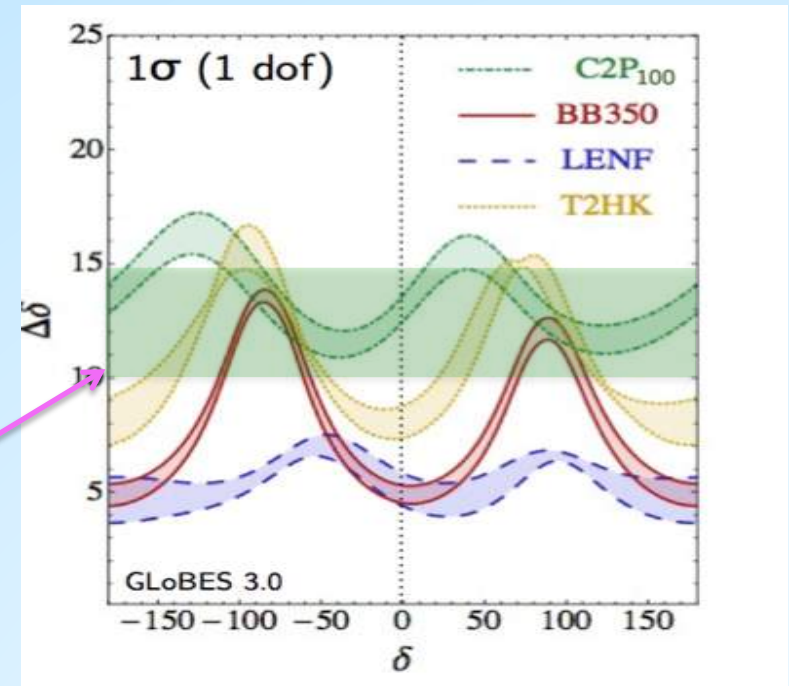
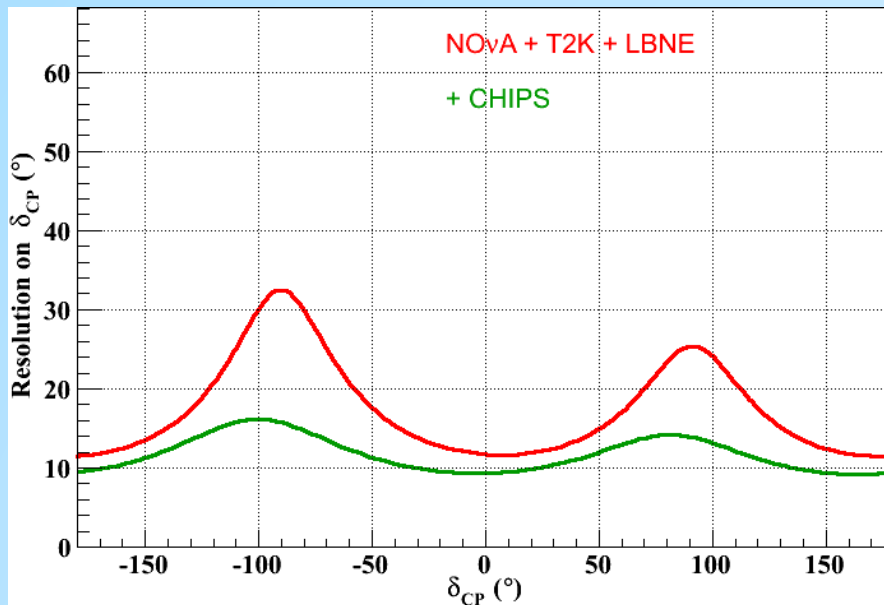


# CHIPS@LBNE



- With CHIPS@LBNE (no NuMI), reach of T2K, NOVA and CHIPS in **2033** (6 years of running after 2027) green shaded region

# 100kt (CHIPS@NuMI + CHIPS@LBNE)



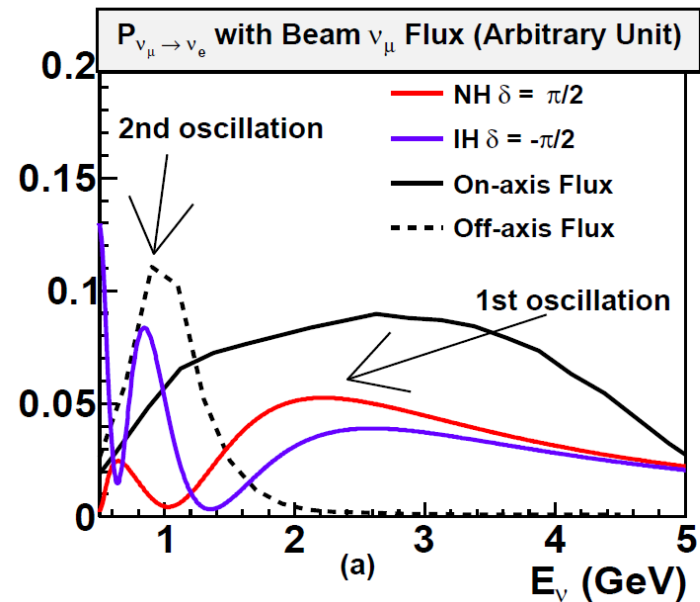
- LBNE could build SUBSTANTIALLY on CHIPS@NuMI and together with CHIPS@LBNE (2035-2037)
- CHIPS can make very big improvement on  $\delta_{cp}$  measurement
- 10kt LAr+100kt CHIPS now on the same page as the NF!
- 20 years to recover from throwing the NuMI neutrinos away..

## Medium Term Goals

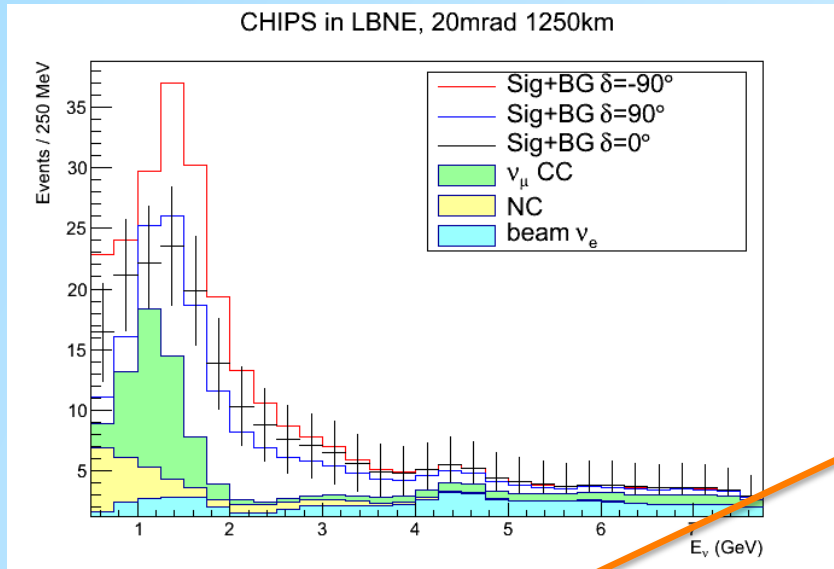
- ~25kt (TBD) vessel to follow on from this proposal (in 3 years time)
- Yearly increase of instrumented mass depending on funding
  - Deployment seasonal
  - Large up-front funding not necessary
  - Staging of detector(s) natural
- All simulations assume 100kt in NuMI for 6 years
- This is the eventual detector mass goal, and hopefully this will be achieved for \$30M (excluding manpower)

## Long Term Goals

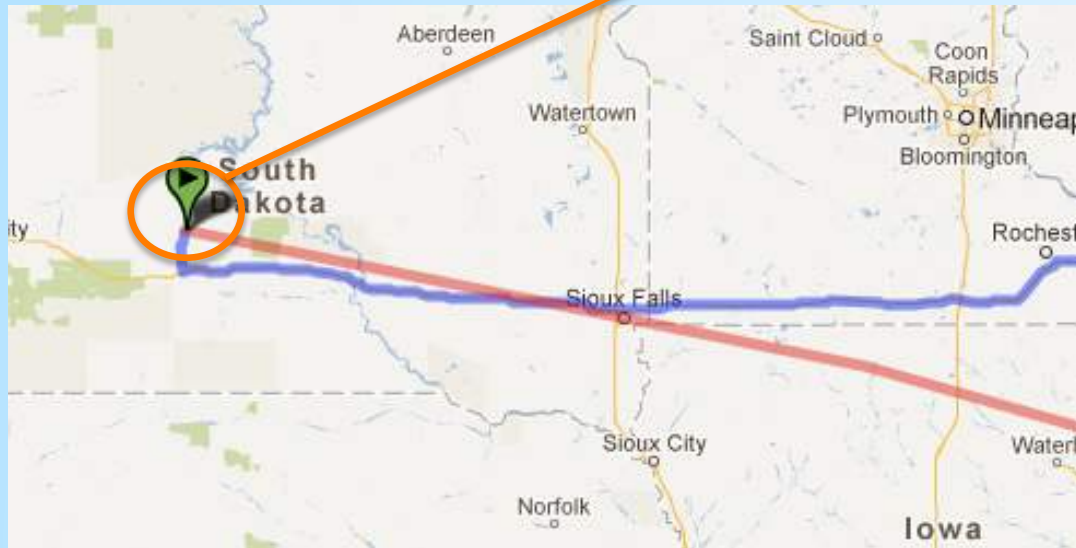
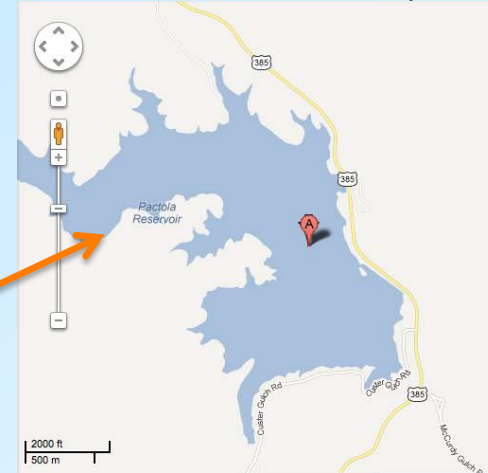
- Idea is to re-deploy CHIPS in LBNE beam off axis
- 2<sup>nd</sup> oscillation maximum located around 0.8 GeV
  - Large quasi-elastic x-section
  - Suitable for water Cerenkov detector
    - High efficiency for QE events



# CHIPS@LBNE (20mr off axis)



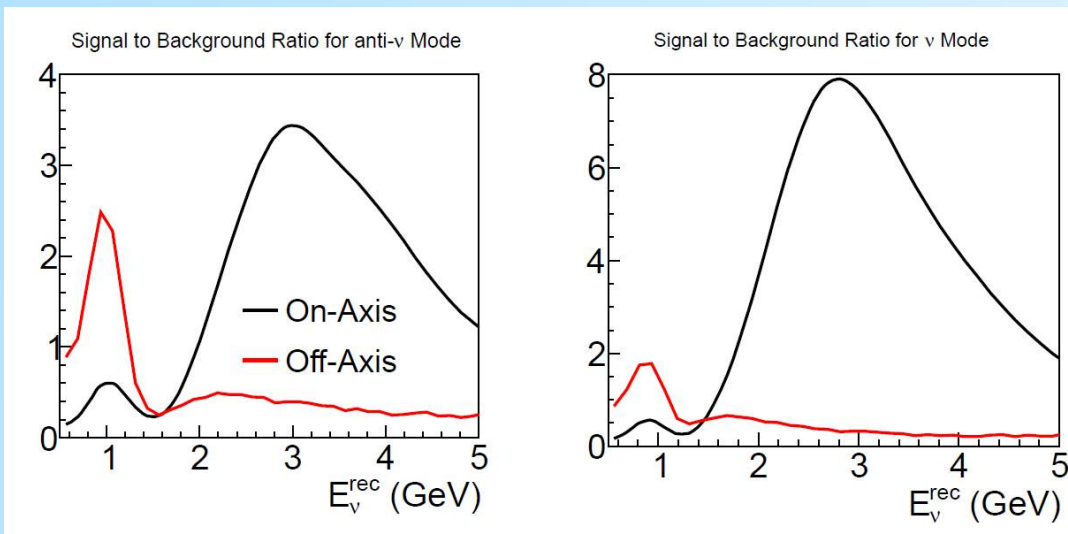
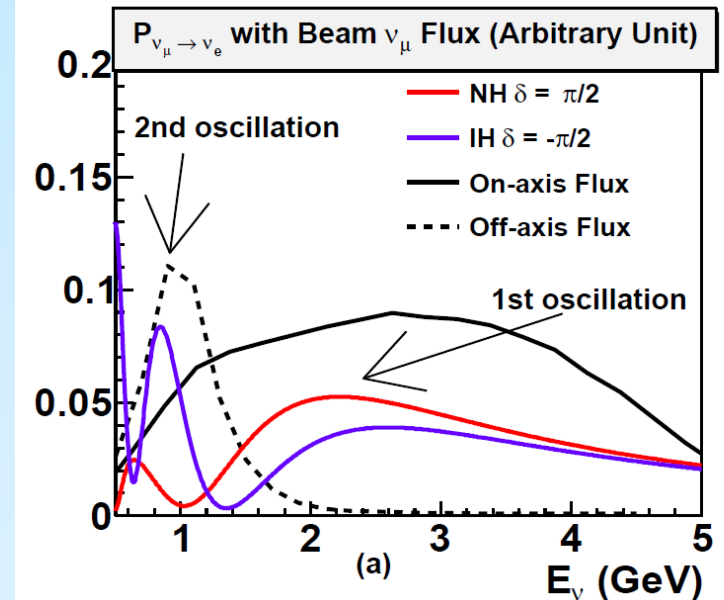
Pactola Reservoir, SD



- There is (at least) one (40m depth) reservoir in the beam line
- If CHIPS in NuMI beam it's a necessary upgrade/augmentation path for LBNF

# Pros of 2<sup>nd</sup> detector in LBNE

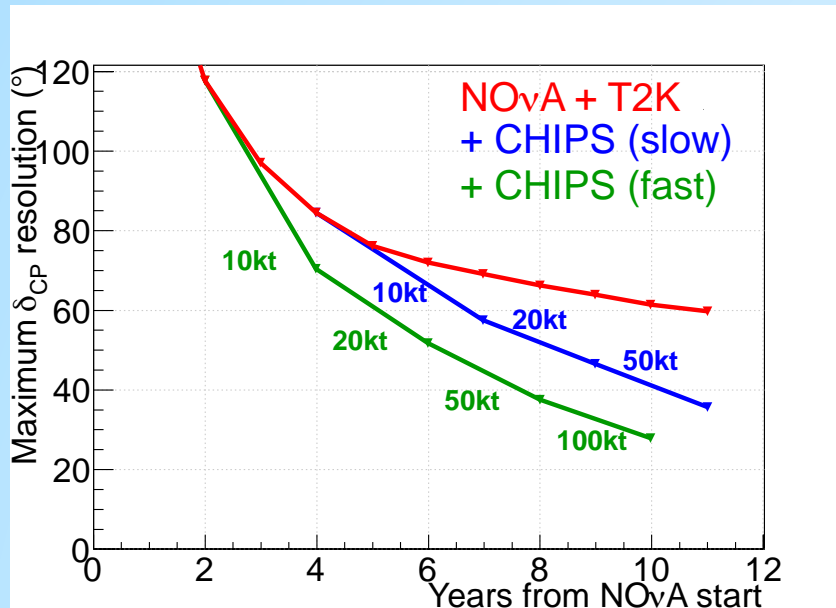
- 2<sup>nd</sup> oscillation maximum located around 0.8 GeV
  - Large quasi-elastic x-section
  - Suitable for water Cerenkov detector
  - High efficiency for QE events



Better signal to noise ratio at 2<sup>nd</sup> oscillation maximum (WC @ off-axis vs. LAr @ on-axis)

# Getting started fast

- Starting small can yield important results if we are fast



- Slow but continuous detector growth (\$3-10M/yr)
- Real costs fully understood using stepwise approach: avoid huge contingencies
- 100kt end result gives impressive gain over NOvA alone

# The Immediate Plan

- First prototype CHIPS-M (Summer 2014, 2015)
  - Working on water 101
  - Test liner, other materials, pump, water filtration, winter
  - Prototype PMT module, KM3net electronics, integration of KM3net and IceCube electronics
- Second prototype CHIPS-10 (Summer 2016)
  - 10kt vessel size
  - Instrumentation mass depends on PMT availability and \$\$
- Final detector CHIPS-25 (Summer 2017,2018)
  - Depends whether we can grow, or whether we have to start afresh



# Status of the project today

- 13 US, 2 UK, 1 Greek institution, about 35 people so far
  - Serious interest from Nikhef
- A three year R&D proposal was submitted to DOE and FNAL PAC
  - Approved by FNAL PAC
  - DOE sent \$100k and a letter requesting a full technical review in April/May 2015
    - The letter also alleviates concerns over P5 “table”
  - Received a letter from IN2P3 promising 400 3” PMTs
  - Interest from Dutch and German potential collaborators
  - STFC still deliberating! Hopefully this will conclude on 25<sup>th</sup> October
  - DOE technical review will be in March/April.
- CHIPS-M is presently under the lake taking cosmic data



This is the fun bit, no plots, just pics!

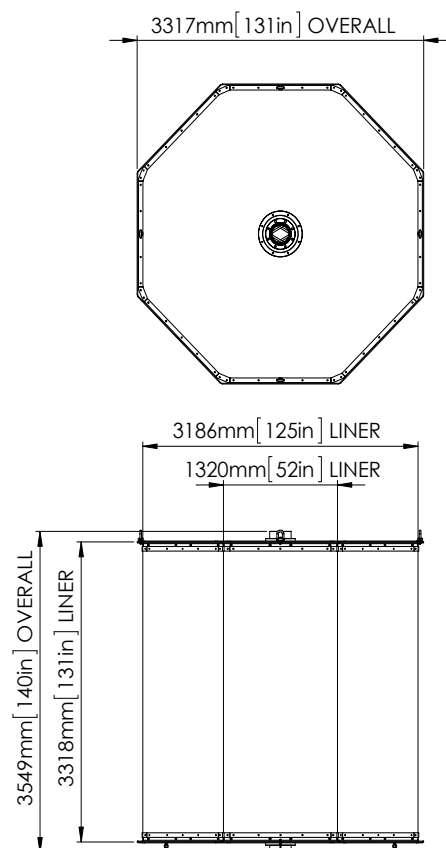
Summer 2014, 50ton prototype

**CHIPS-M**

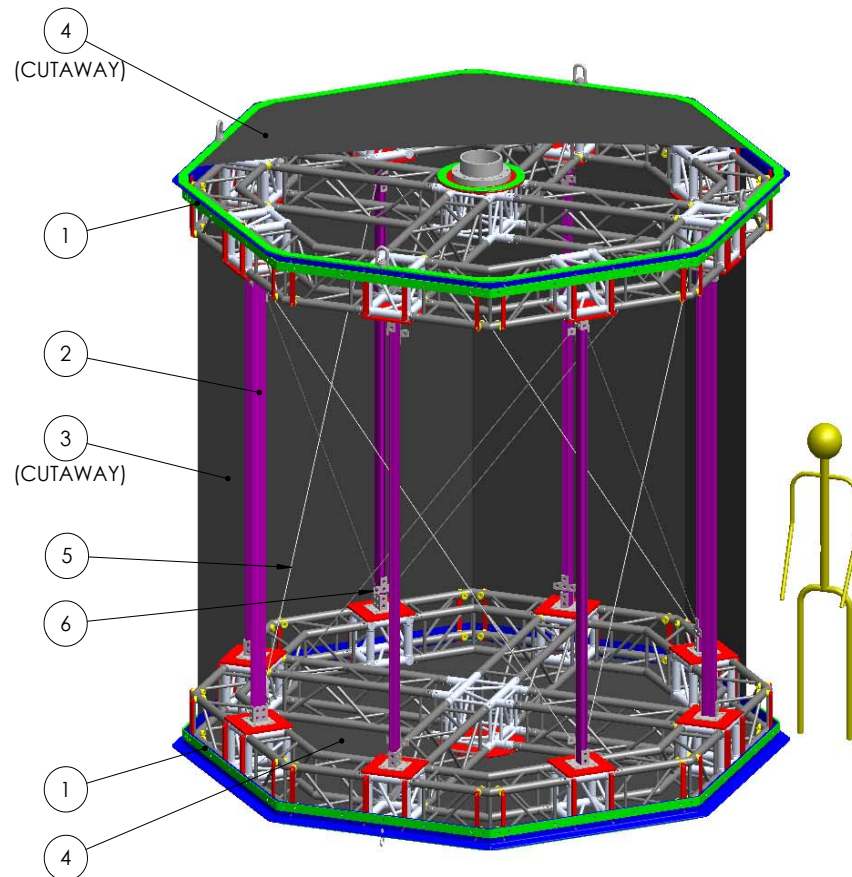


# CHIPS-M being designed

ITEM NO.	DESCRIPTION	Material	Vendor	QTY.
1	End Truss Assembly			2
2	Column	304 SS Double Strut Channel (Back-to-Back), 120in stock (cut to length)		8
3	Wall Liner	Seaman XR-5 PW		1
4	End Liner	Seaman XR-5 PW		2
5	Lateral Bracing Wire Rope Assembly	304 SS, 1x19 const, 3/16in dia, ~132in length	McMaster p/n 3461T18 plus end hardware and turnbuckles	8
6	Strut Channel T-Plate	304 SS		8



EST. DRY WT. 1500 lb  
EST. WET WT. 970 lb



MATERIAL	ASME Y14.5M 1994 APPLIES	DATE	3.27.14		
	UNLESS NOTED UNITS: INCH	DRAWN	TLB	CHK'D	-
CHIPS-M STRUCTURE 3.27.14	3-PLACE: +/- .005	APPR'D	-	NO REQ'D	-
	2-PLACE: +/- .010	SCALE	1	OF	2
USED ON	1-PLACE / FRAC: +/- .015	ANGULAR: +/- 0.5 DEGREES	SHEET 1 OF 2		

**PHYSICAL SCIENCES LABORATORY**  
UNIVERSITY OF WISCONSIN  
(608-877-2200)

DRAWN WITH SolidWorks

# CHIPS-M being constructed

- Parts built at W&M, constructed in Soudan surface building
- Dedicated team of youngsters : 1 postdoc, 3 grad students, 5 undergrads

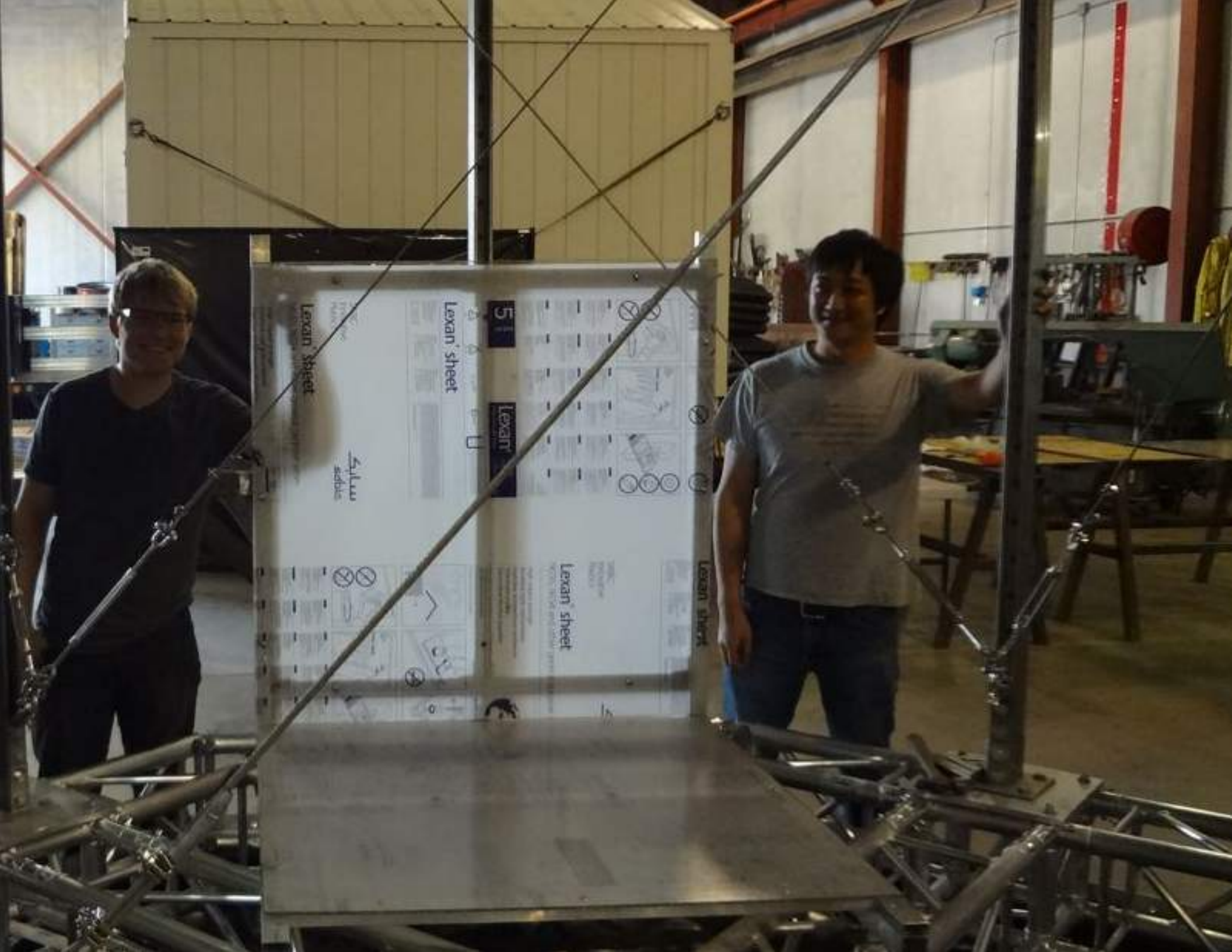




# CHIPS-M being constructed











# Hard Work

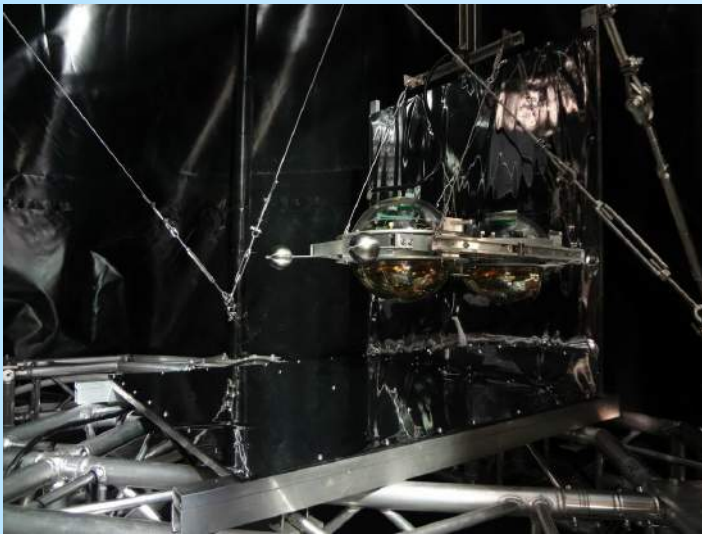
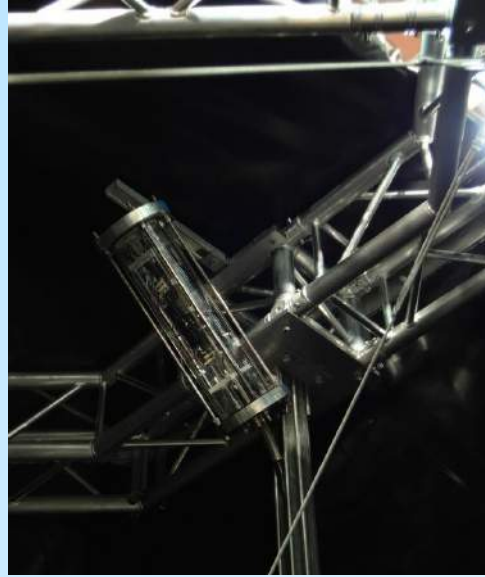
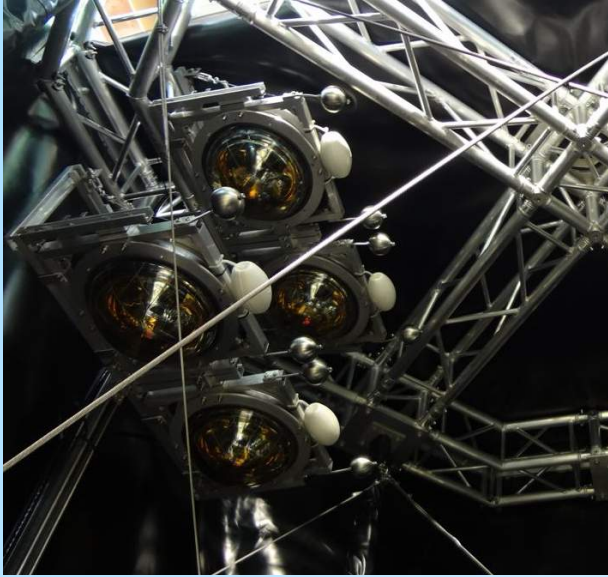


# Hard Work





# IceCUBE DOMS and camera inside



# Cable/hose feed through









# Moving Day



# A lovely picture







cruelty', including gang rape and ethnically motivated murder, says Human Rights Watch

## K sleuth and wife appear in court



Briton and wife Yu Yingzeng in first formal hearing since being accused of illegally getting information on Chinese citizens

## Lowy anti-Israel speech inquiry



Police alerted after Respect MP declares Bradford 'an Israel-free zone'

## n fined for pretending to be ghost



Police spokesman says witnesses complained about Anthony Stallard 'throwing his arms in the air and saying woooooo'



## Film review God's Pocket



**John Harris**  
Ukip has not gone away – don't be fooled by the lull



## Photography



## The man who walked the Nile

Former British army captain Levison Wood attempts to be first person to walk entire length of the river

## My favourite physics snaps



**Jon Butterworth** picks out his top recent (and not-so-recent) science-related shots

5 comments



# Recreational Activity

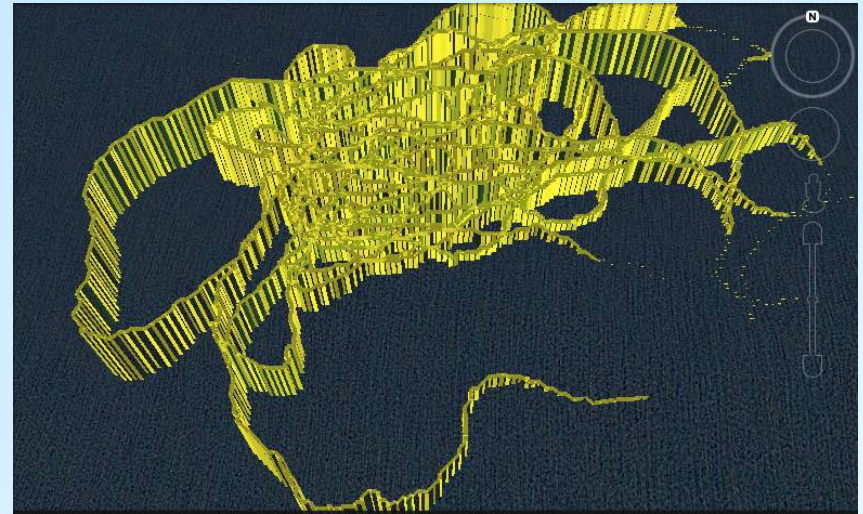


# Water Clarity





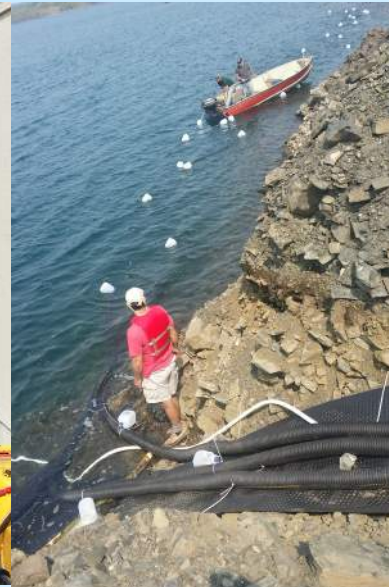
# Where to put the detector?





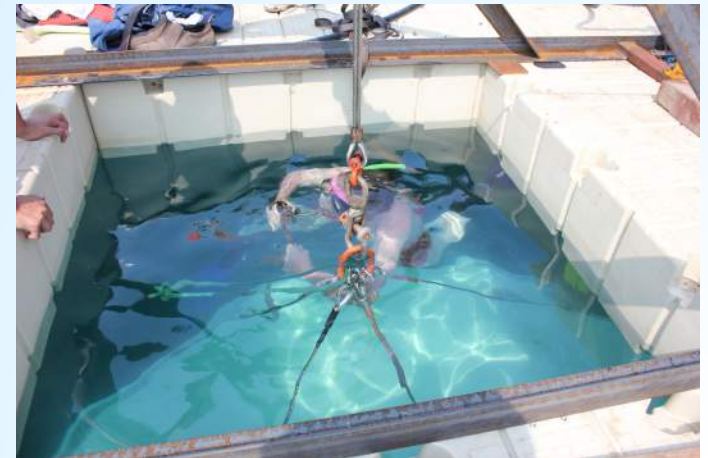


# Umbilical: carried water and signals





# Deployment Day



# A moment of calm and beauty





# Zoom In!



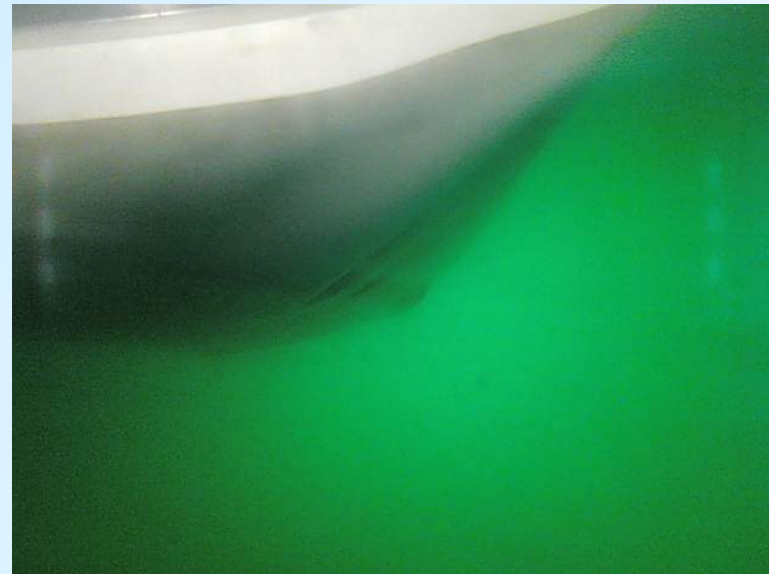
# Environmental Monitoring



inside



outside







# The Control Room





# The Water System

- UV Sterilizer
  - Series of filters down to 0.2microns
  - Carbon filter to eliminate life
- Air purging was very difficult
  - Added a second jet-pump
  - Circulates at 3-5gpm





# Then, one day....



**And eventually....**



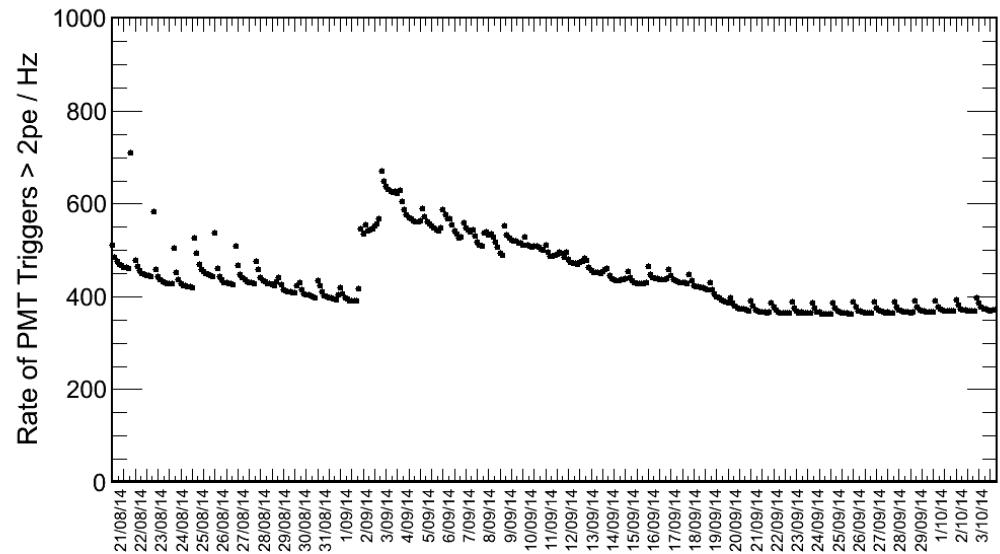
# CHIPS-M Data

- Top plot shows trigger rate

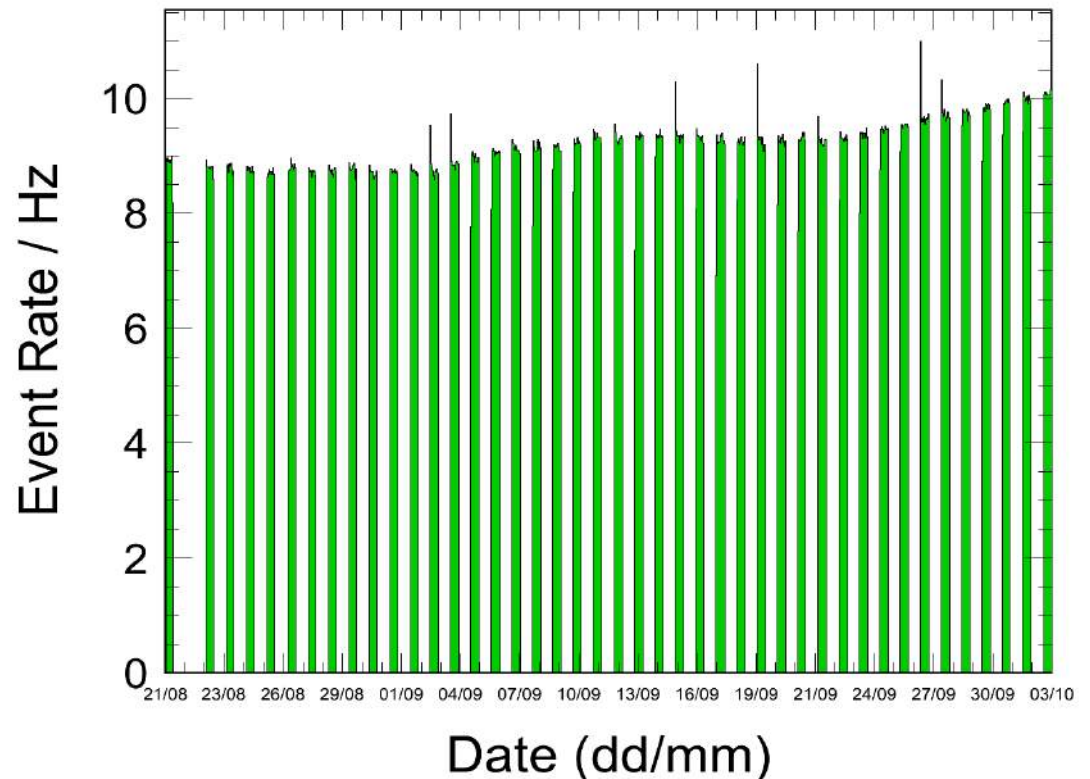
- Run overnight only
- Light leak apparent
- Jump coincides with full moon

- Bottom plot shows real events

- 4 PMTs hit in coincidence
- Slow rise could be effect of water
- Continuous monitoring will tell
- Rate is 9Hz: estimate is that there should be 350Hz cosmic rate
- PMTs are facing down, rejection rate 350/9, factor 35
- 35 Hz 2 hit rate, 18Hz 3 hit rate



Rate of 4-hit coincidences (>5p.e.) over time





# Attenuation Measurements

- CHIPS has advantage of being under about 6 bar pressure
- 4 degree temperature ensures bacterial blooms will not be a problem
  - According to our expert who provides the system for SuperK
- Filters provide
  - a raking of the particulates in the water down to 0.2 micron
  - A carbon filter to eliminate life + a UV sterilizer to make sure
- Bubbles are crushed and will not be as much of a problem as at SuperK (not under pressure)
  - Bubbles produce scattering centers which contribute to the attenuation by scattering light away
  - Scattering length is reasonably straightforward to measure in-situ with a laser
  - However, absorption length very difficult to measure on the surface in the lab as the bubbles enlarge
    - Super-K biggest problem is bubbles, not a problem under 2km of sea
- We can measure overall relative attenuation length with in-situ LEDs
  - Presently LEDs on the IceCube DOMS can be flashed
  - We will cross calibrate that to water measurements ongoing at UMn and UMD which measure attenuation length on a sample of water
- Measure absolute attenuation length (maybe) and subtract scattering length to give absorption
- Needed for simulation benchmarking, but in the end it is what it is

# A look back to January 2014

## WBS 1.11: Integration and Deployment

- Integration will first happen at the Soudan Surface building
- Presently we are relying on an army of volunteers for the commissioning: undergrads, grad-students, post-docs and academics to save money
  - Experience for students almost without comparison!
  - This should allow many hands to make light work
  - The guys in charge would be professionals
    - Safety and construction training essential beforehand
    - Military training obviously an advantage 😊

## WBS 1.12 : Commissioning

- Commissioning will take place with undergrads, grad-students, post-docs and academics
  - Only 5 DOMS to bring to life
  - Analysis of data much more time consuming in the first instance, and to pick out the beam spill will be very challenging
    - We expect about 100 muons / year from the beam
  - Another great learning experience for the students

# Summer 2015

- Test Photodetector Assembly module
  - Including Km3Net electronics board
  - Km3Net cable
  - IceCube underwater assembly board?
- Test mechanical structure module
- Inspect CHIPS-M
- Identify any failures in
  - Liner
  - Pressure/temp sensor units
  - Materials
- Understand light leaks

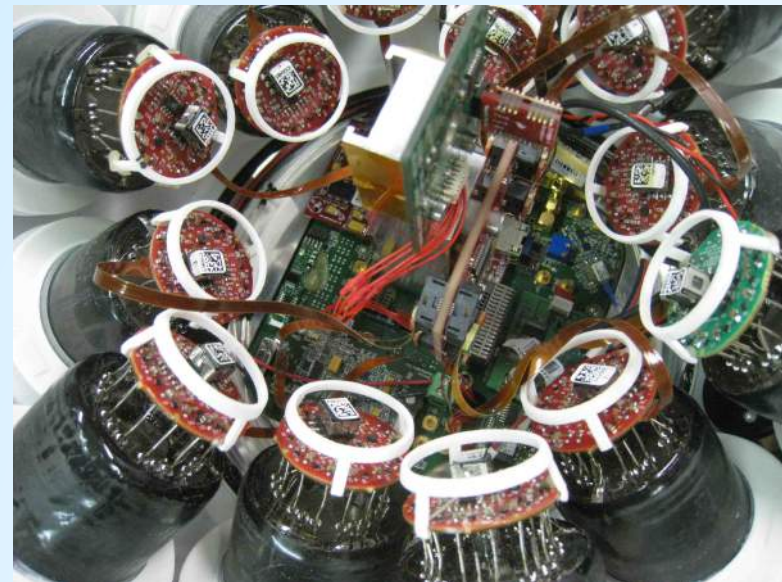


# The next year

- Various electronics are out there
  - KM3Net have a 31 PMT board with CW on the bases which delivers ToT via ethernet
  - ParisROC ASIC has been developed for 16 PMTS: we will look at that also
  - IceCube DAQ will possibly be integrated also, so we can have flexibility of using IceCube spares, also good for PINGU.

# KM3NeT optical modules

- 31 PMTs of 3in diameter :
  - About the same cost as 11" (per unit photocathode area)
  - Much more competition for these tubes (medical industry)
- Mounted in a structure produced by a 3D printer
- Low-power Cockroft-Walton HV generator
- PMT signals processed locally using a specially developed ASIC and FPGAs.
- Time-over-threshold instead of waveform digitization
- Very thick glass DOM would be replaced with thinner acrylic
  - Two wires (power)
  - Two optical fibers
- The PMT-base developed at Nikhef, the central logic board (CLB) at Genova (board layout) and Nikhef (fpga firmware) and Saclay contibuted CLB prototypes.



# Inner components

Winston Cone or simple mylar collar would increase effective collection area by up to 30% for small increase in cost



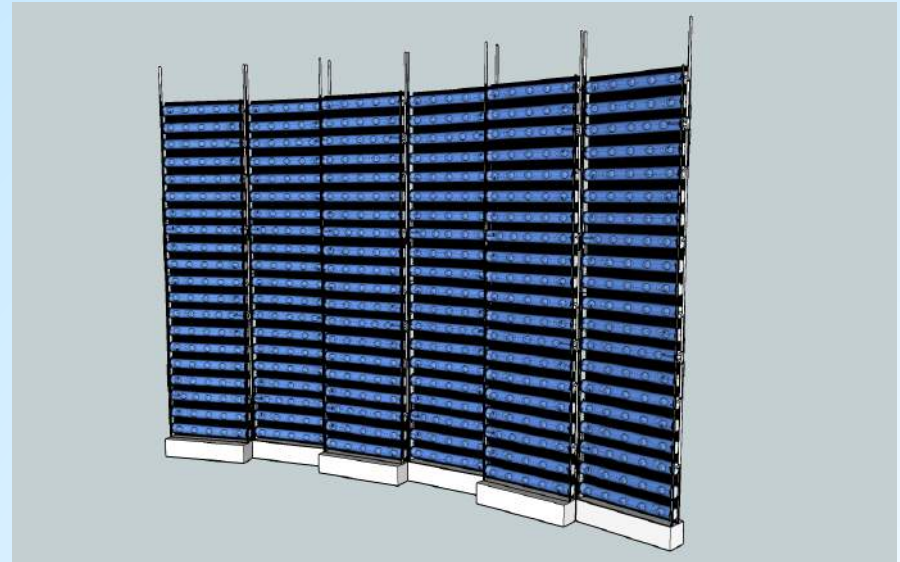


# Mechanical Design

- Work on going on the mechanical design
- Possibilities are likely modular
  - Bolt together pieces which integrate liner and structure
  - Separate plates of PMTs (think egg box?) which bolt on
- Structure will be built on the water with a large floating dock piecewise
  - Model is to use undergraduate labor a la NOVA for both module construction and integration
- Neutral buoyancy will be designed in to each module

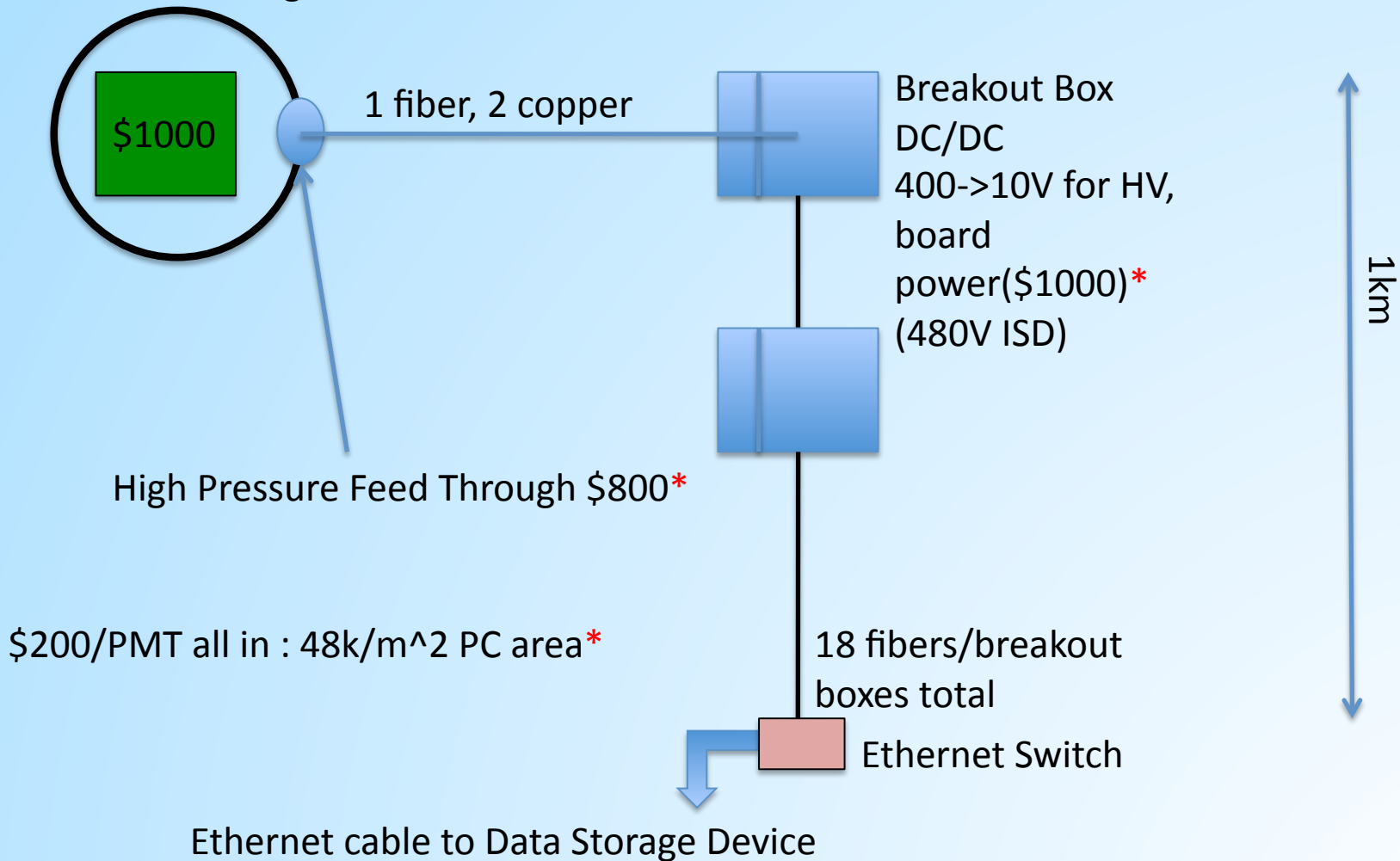
# PMT Sub Module (PSM)

- This is our present concept
- We will make some prototypes using our 3" tubes, and prototype electronics from KM3Net
  - Discussion started with Nikhef for access to some early prototypes
- Read them out together with DOMs



# KM3Net relevant electronics

HV generation on the base and TOT  
digital conversion





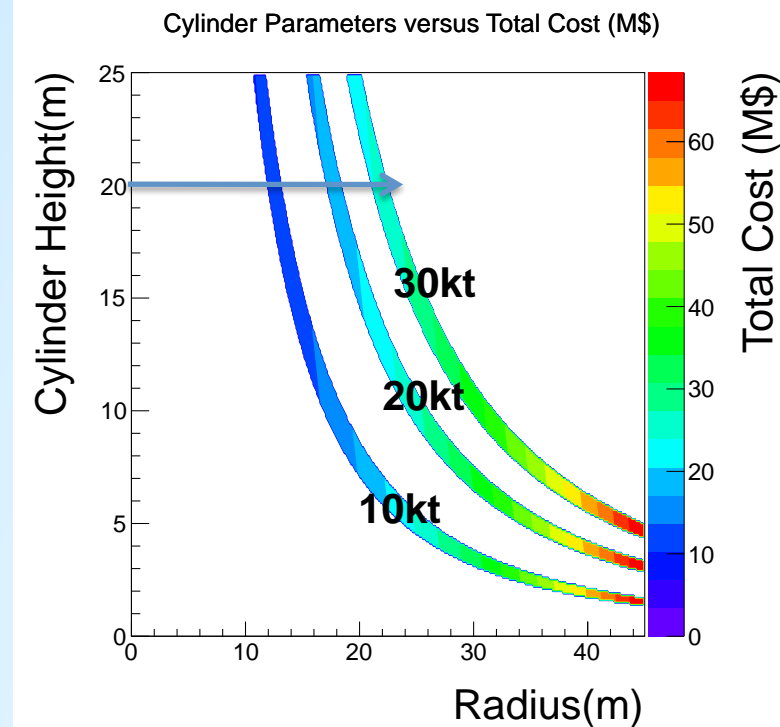
# CHIPS costings

- CHIPS-10 calls for 5000 10" PMTs \$92k/m<sup>2</sup>, 10% coverage
- CHIPS-25 calls for 13000 10" PMTs, costs based on 12" Ice Cube experience
- This for uniformly tiled inside surface

Item	Cost per Channel
PMT, 12" HQE	\$1,800
Frame Housing	\$34
Base Encapsulation	\$93
HV Base	\$34
HV Supplies	\$45
Front End, trigger, DAQ	\$80
Cables	\$150
PIU (support framing)	\$200
Total per channel	\$2,436
Total 13K channels	\$33,750,000
Engineering Cost	\$3,000,000

Table 4: Cost of the PMT assemblies

Item	First 50 m×20 m module (D×H)	Additional modules
Engineering	\$1,000,000	\$200,000
Marine Cage Superstructure, 3 rings	\$250,000	\$250,000
Steel framework for liner support	\$1,000,000	\$1,000,000
Liner (\$50 m <sup>-2</sup> )	\$500,000	\$500,000
Deploy PMT modules, 9 FTEs	\$900,000	\$600,000
Water Purification System	\$1,400,000	\$1,400,000
Total	\$5,050,000	\$3,950,000

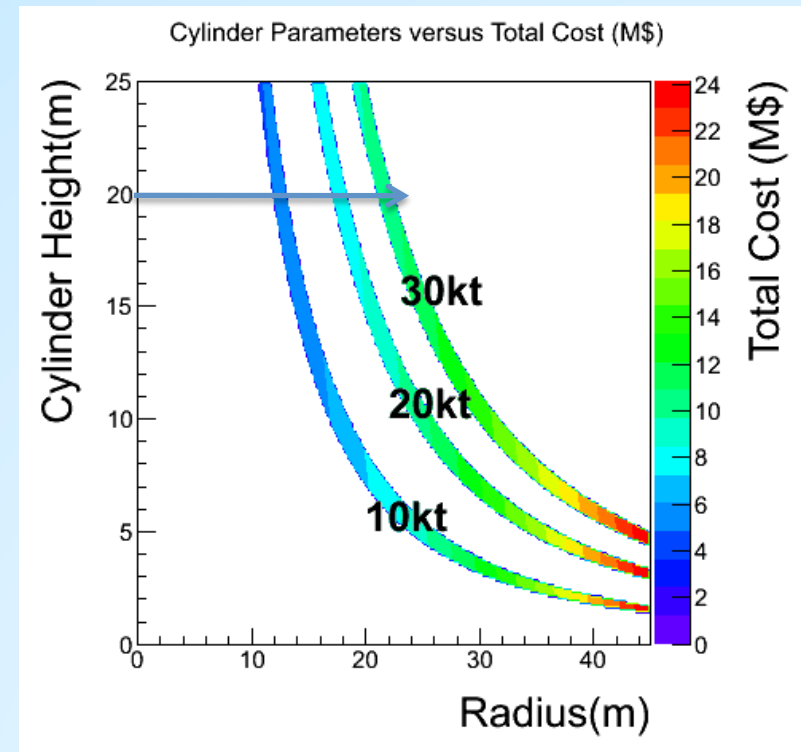


# CHIPS costings

- CHIPS-10 calls for 60,000 3" PMTs, 47k/m<sup>2</sup>, Km3NET costings
- CHIPS-25 calls for 130,000

\$200/PMT all in  
Reduce cost by not  
instrumenting back face as  
densely

Item	First 50 m×20 m module (D×H)	Additional modules
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Total	\$5,050,000	\$3,950,000



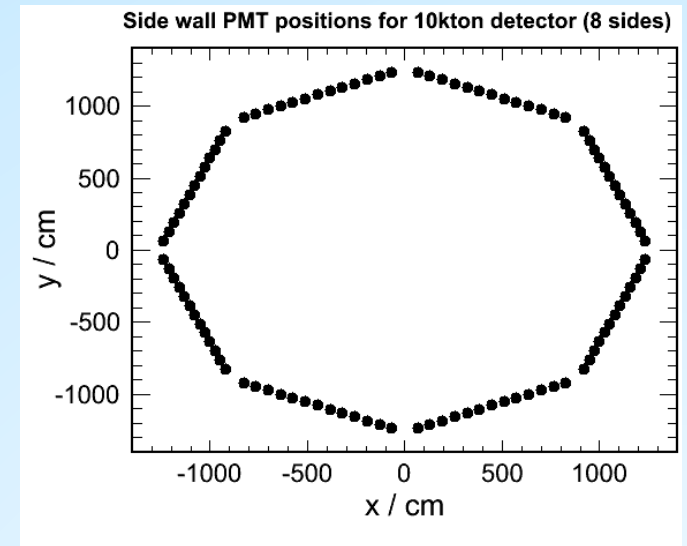
# Simulation has progressed

- New features allow pattern of different PMTs throughout the detector
  - First time this has actually been properly simulated,
  - Optimal layout of PMTs will be understood before PA modules go into production: this will be by end of 2015.
- Reconstruction based on miniBOONE algorithms has been developed and is being tested
  - Includes charge and time likelihood pieces

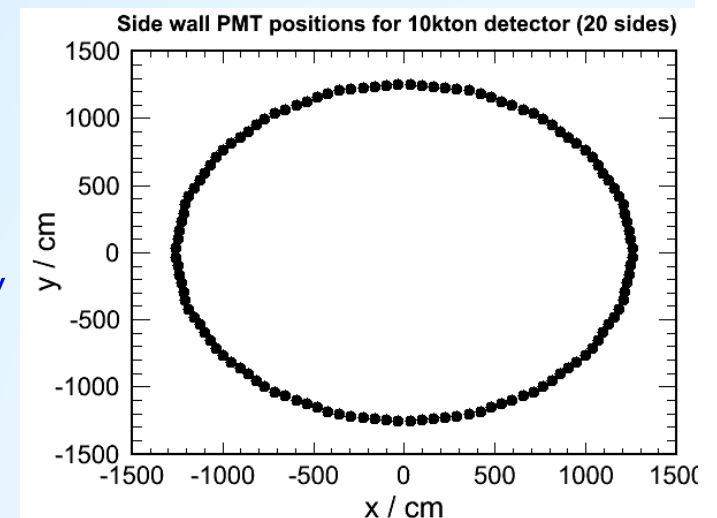


# Simulation

- Use Geant4 simulations to guide the design process
- Software originates from WCSim:
  - Program to build generic WC geometries
  - Tuned based on Super-K data
  - Developed for LBNE design studies
- Has since been heavily modified to introduce new features:
  - Completely rewritten the detector construction routine that creates an n-sided prism
  - Run-time description of geometry and PMTs using xml files - make changes without recompiling
  - New PMT simulation with full dynode chain
- Event generation with Genie using the medium energy NuMI spectrum

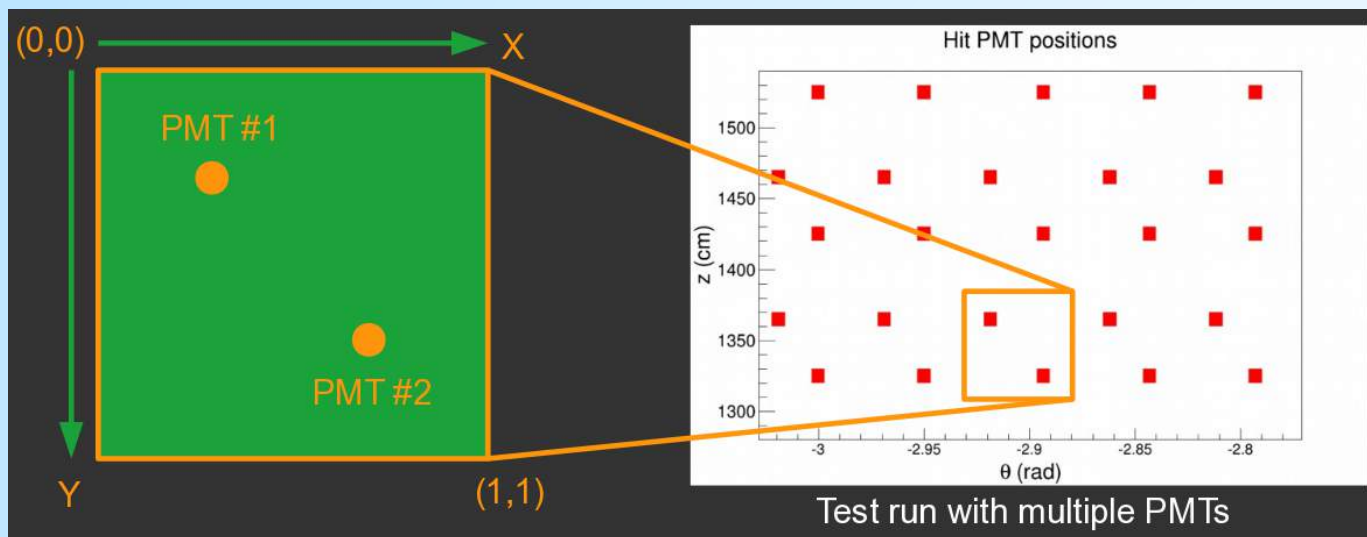


Geometry specified at run-time with xml files



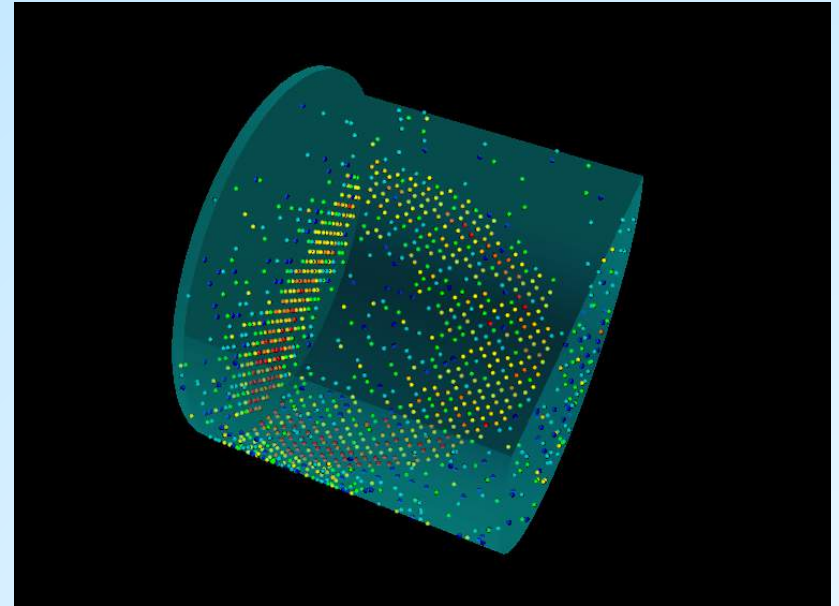
# PMT Layout

- New feature to lay out PMTs in more complex patterns
- Model the effects of different-sized PMTs side-by-side
- Use xml file to describe a "unit cell":
  - Specify PMT types, and their place in a 1 x 1 square unit cell
  - Cell is scaled and tiled round the detector to give the desired photocathode coverage



# Future

- Allow PMTs to be combined inside larger objects:
  - e.g. one module holding a strip or hemisphere of small PMTs
  - or a string of PMTs throughout the volume instead of on the walls
- Add measured properties of our own liner material, pit water etc.



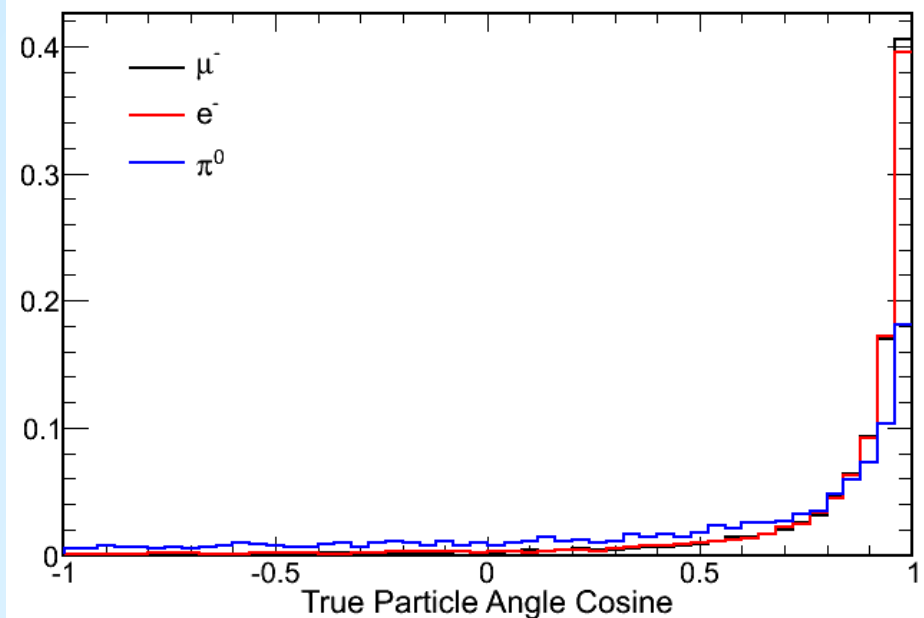
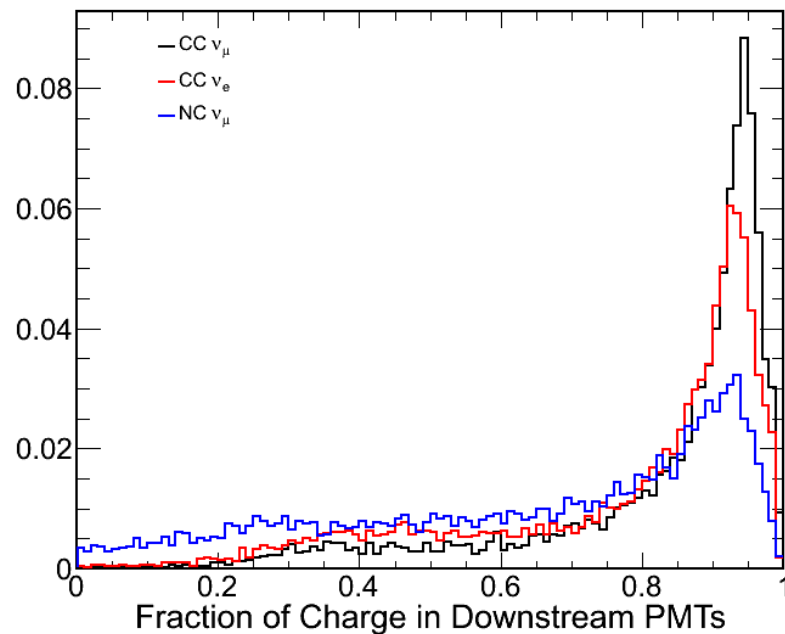
Cut-away event display showing the muon ring from a  $\nu_\mu$  CC event with the 2 PMT per cell layout from previous slide

Combine simulation with our actual full reconstruction framework to make detailed studies of the PMT layout and design decisions



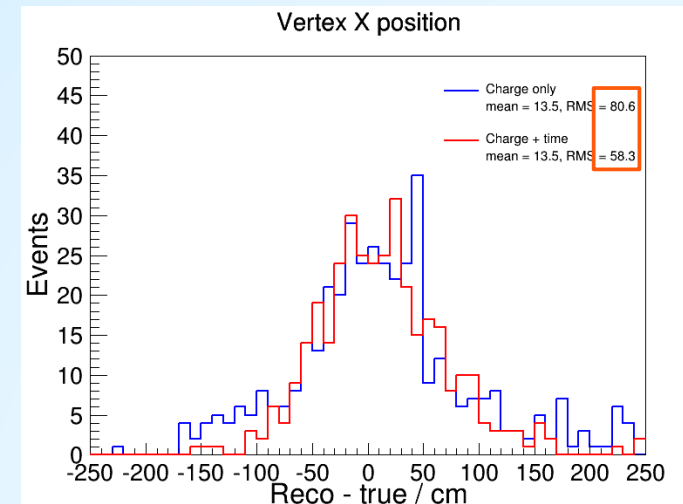
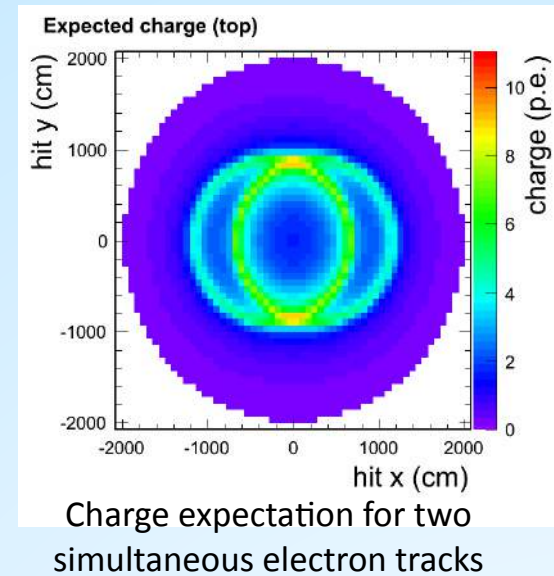
# Simulation studies in new framework (WCSIM extension)

- GENIE generated events in the water
- Right shows the angle cosine wrt the beam axis
  - Much longer tail for the  $\pi^0$
- Left shows fraction of charge in downstream PMTs
  - All NC events, not just the  $\pi^0$



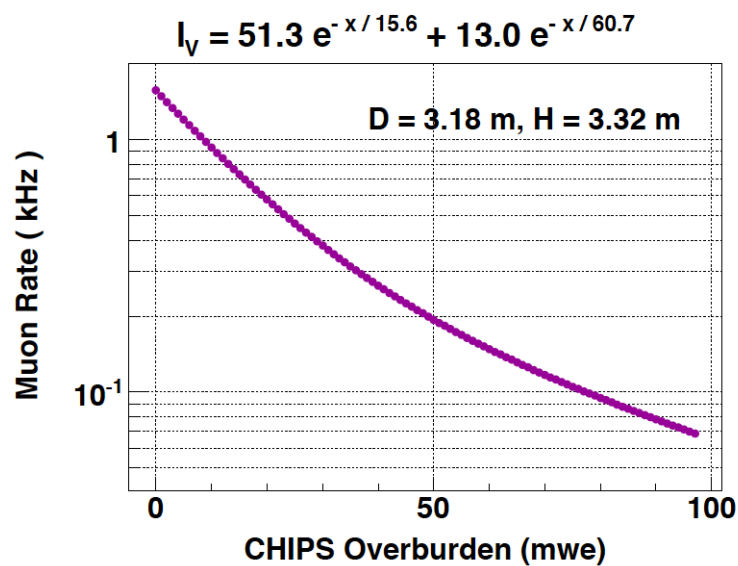
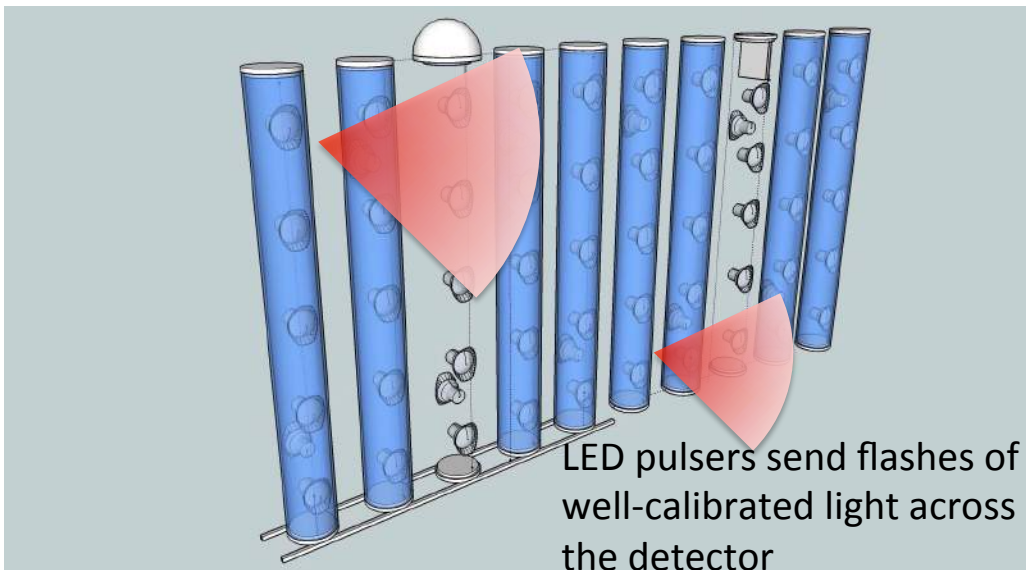
# Reconstruction Status

- Can calculate the likelihood for a given combination of track hypothesis and hit pattern
  - Uses data from simulation as the input
  - Works for multiple tracks
- Preliminary fitter is working, varying all the track parameters except energy
  - Shape of the ring varies with energy
  - Working to make the minimizer manage with these correlations
- First fits combining both charge and time information show an improvement over charge-only



Fit results for isotropic 1.5GeV muons in a 20kton detector with 10% coverage

# Calibration Plans



Through-going cosmic muons provide a day-to-day stability measurement

Stopping cosmic muons provide an absolute energy scale based on well-understood energy loss rate through water



# Calibration Plans

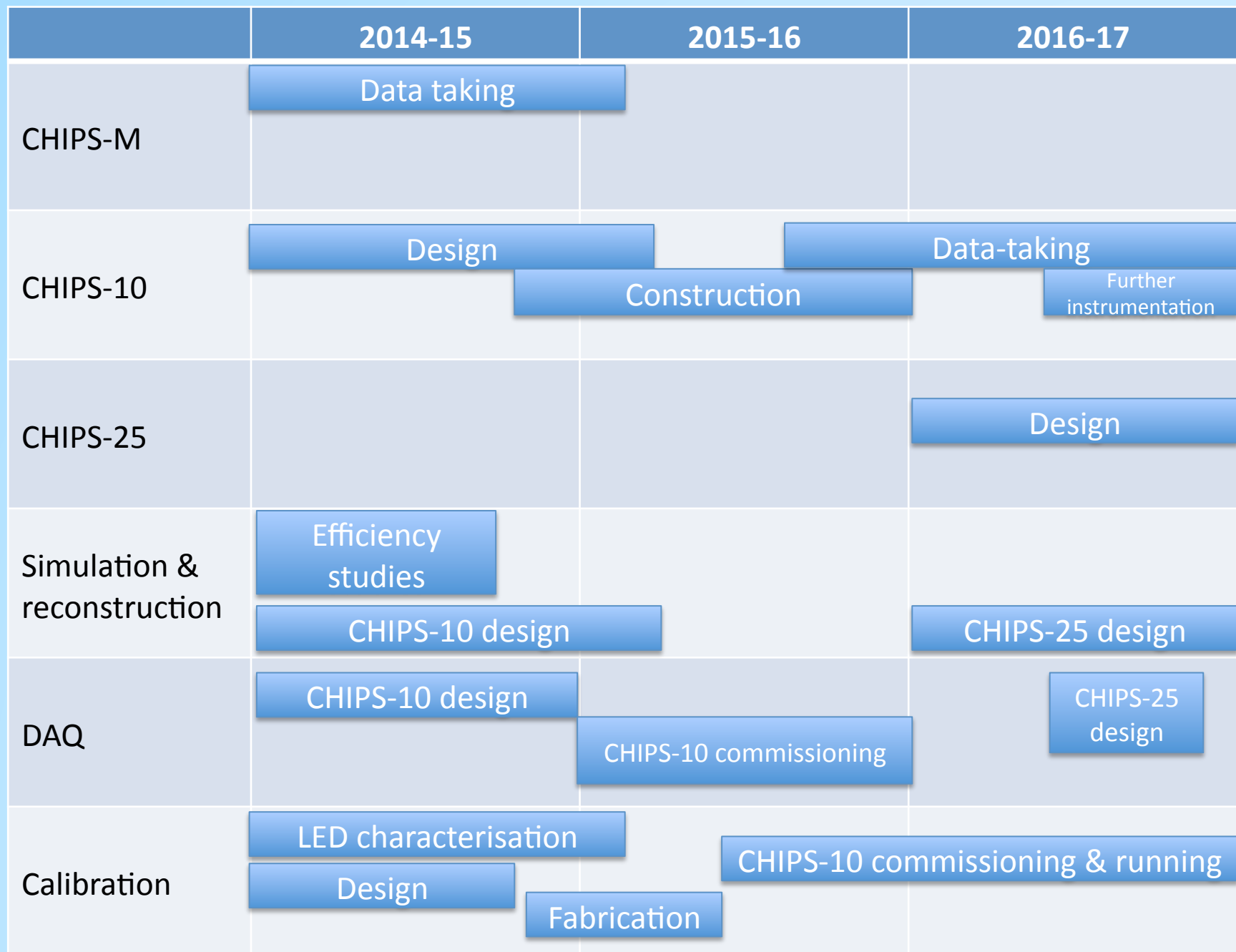
- Development of monitoring of water clarity
  - Using lessons learned from CHIPS-M and KM3Net
  - Need blue/green (!) laser(diode)/collimated LED to measure and monitor scattering of light
    - This should improve with filtering and recirculation
  - Need LEDs to monitor overall attenuation
    - Hopefully this will be slowly improving over time
  - LED flashers will monitor single PMT gains
    - These can be individually controlled from control shed via KM3Net board.
  - Laser diode in-situ for scattering measurements

## Summer 2016

- Plan is to deploy 10kt vessel
- ~30m diameter structure with possibly up to 8m<sup>2</sup> of PC area of existing tubes
- Will purchase tubes as per available cash
- We need about 120m<sup>2</sup> of PC area for ~10% coverage assuming back is sparsely covered

## Summer 2017

- Order for rest of tubes (or some fraction of them) must go in in the next year to be ready for Summer 2017
- ~2000 10” equivalent tubes will be needed for most optimistic full coverage



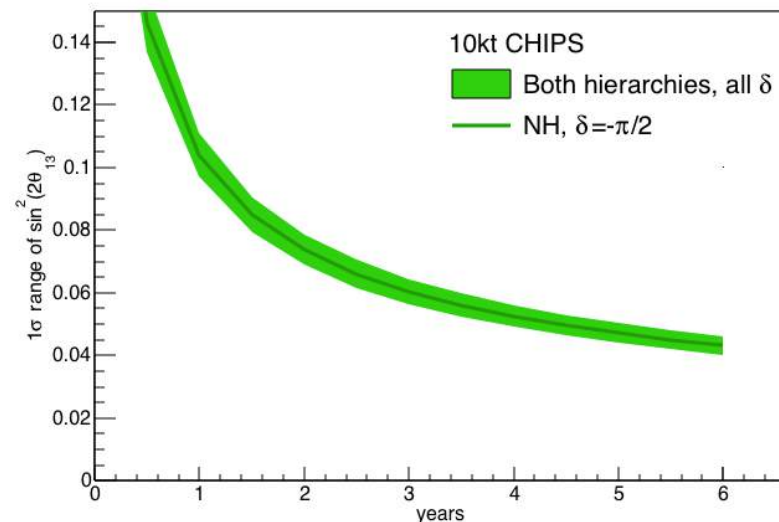
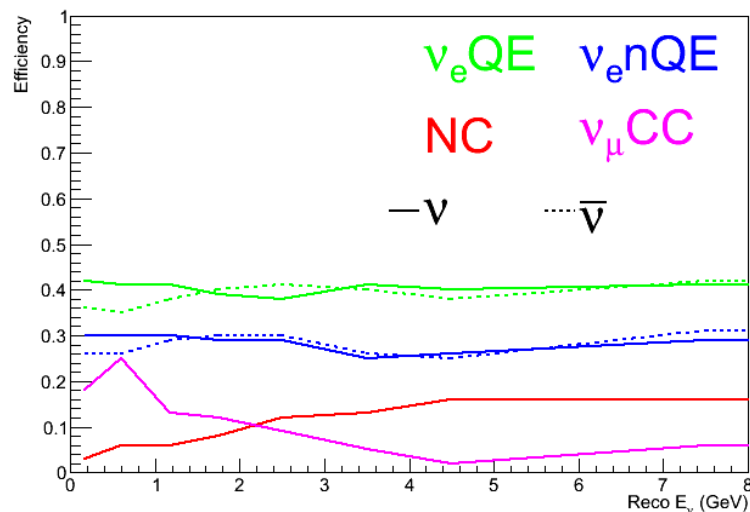


# Deliverables by end of 2017

- CHIPS-10 in the water (1.1,2.11,2.14)
  - Full DAQ (2.9) and calibration(2.8) systems deployed
  - Some combination of different PMTs arranged in the optimum pattern for the beam neutrinos (2.4)
  - Identification of any PMT characteristics which make one type of tube stand out (2.7.4)
- Identification of  $\nu_e$  and  $\nu_\mu$  CC events (2.4,2.12)
  - Measurement of  $\theta_{23}$ ,  $\theta_{13}$  (2.12) (see next slide)
- Conceptual design for CHIPS-25 (2.13)

# Hopes and Desires

- by 2017 we hope to have 10kt instrumented in the water
  - Two actual deployment seasons (2016, 2017)
- We hope to have proved the background rejection at a level of or better than expected
- We hope to be able to see non-zero  $\theta_{13}$



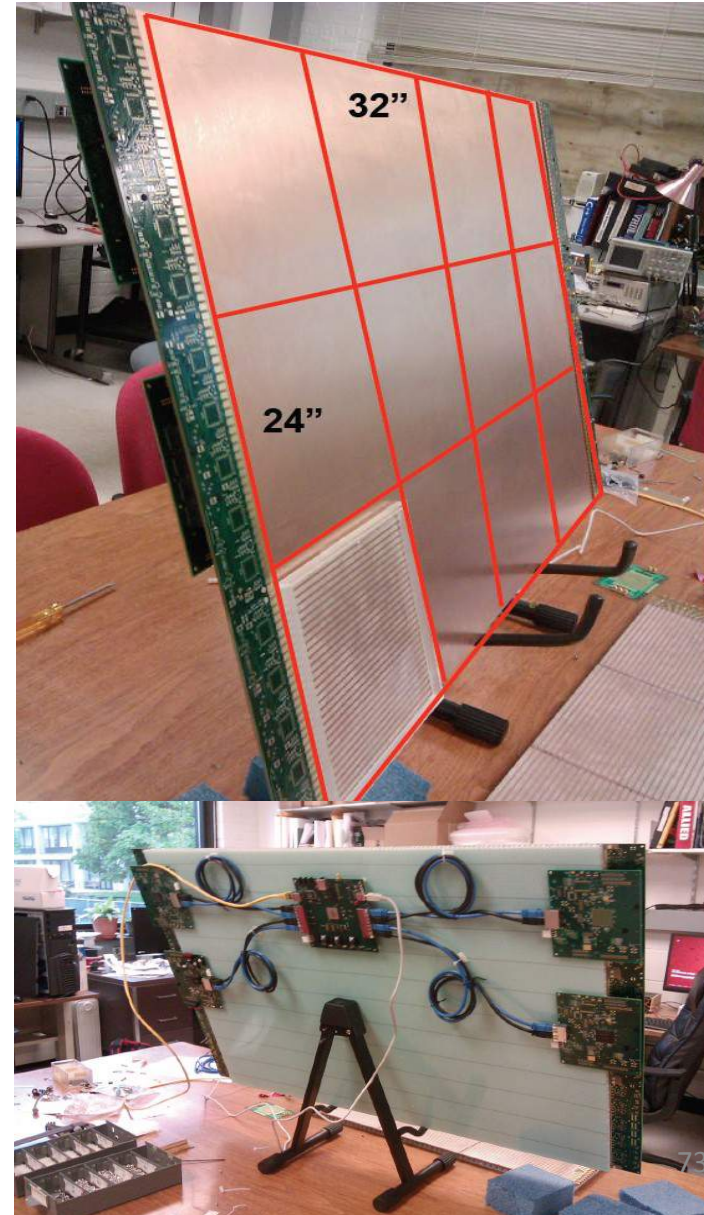
# Longer term future

- The main cost driver is the PMTs
  - Total of 5048: 3240 on barrel, 904 on each end cap 10", 10%
  - Reductions possible due to configuration
- In the short term try to borrow as many as possible
  - This ~works for first year of CHIPS-10, but not more
  - We have to continue to push on PMT costs
    - We could be a very big customer !!!
  - 3" PMTS could come in at \$100/pop
  - There are hybrid PMTs (apd instead of base)
  - Similar idea using MCP from the Chinese
  - Also other developments may become relevant



# Next: LAPPD for Neutrinos

- Micro-channel plate photosensor in 8" x 8" tiles arranged in 24" x 32" super-module
- 100 psec time resolution / 1 cm spacial resolution
- Channel count optimized to large area/ desired granularity
- Integrated double-sided readout
- Scaled high QE photocathode
- Large area flat panel provides robust construction. Low internal volume and use of known glass.
- No magnetic susceptibility



# Summary

- The CHIPS R & D program has started with a major contribution from all the collaborating universities including UCL and Manchester, and notably University of Minnesota, Fermilab (via Soudan Mine Crew), DOE and STFC.
- Funding for future effort has been received from UK (Leverhulme), awaiting STFC decision
- DOE Technical design review due in March/April
- CHIPS-M was deployed, monitoring continues